ESIG
Large Loads
Task Force

Large Load Performance Requirements

CURRENT PRACTICES AND RECOMMENDATIONS

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

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ESIG
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Large Load Performance Requirements: Current Practices and Recommendations

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

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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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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 listed here:

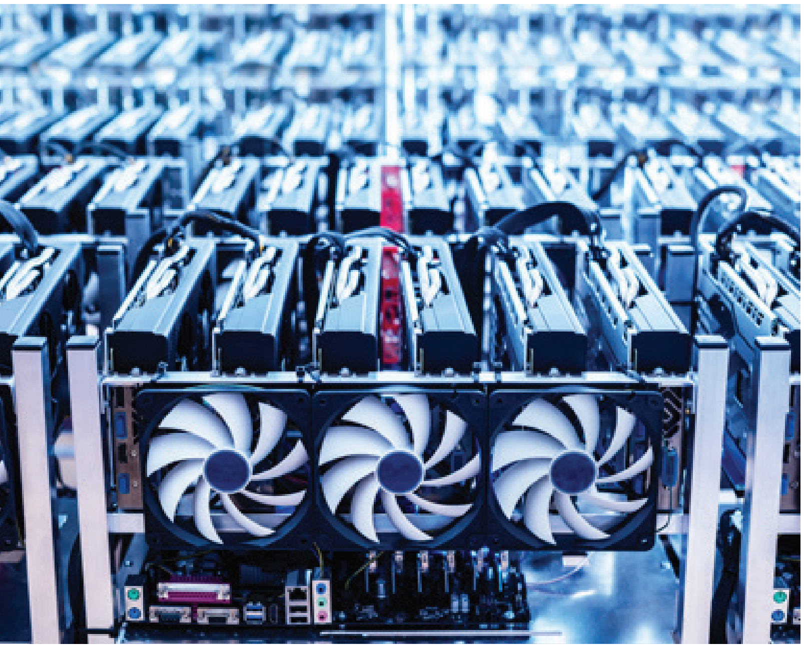
- Grid Integration of Large Loads: Introduction to the Large Loads Task Force, Data Needs, and Flexibility Overview
- Forecasting for Large Loads: Current Practices and Recommendations
- Interconnection Processes for Large Loads: Current Practices and Recommendations
- Large Load Performance Requirements: Current Practices and Recommendations
- Large Loads: Behaviors, Capabilities, and Limitations
- Reliability Impacts of Large, Power Electronics–Interfaced 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

Contents

Abbreviations

ACE	Area control error
AESO	Alberta Electric System Operator
AI	Artificial intelligence
APR	Active power recovery
ATC	American Transmission Company
EMT	Electromagnetic transient
ERCOT	Electric Reliability Council of Texas
FRT	Frequency ride-through
GPU	Graphics processing unit
HVDC	High-voltage DC
HVRT	High-voltage ride-through
IBR	Inverter-based resource
IESO	Independent Electricity System Operator
ISO	Independent system operator
ITIC	Information Technology Industry Council
LVRT	Low-voltage ride-through
NERC	North American Electric Reliability Corporation
PLL	Phase-locked loop
PMU	Phasor measurement unit
POI	Point of interconnection
PSPD	Positive-sequence phasor-domain
RMS	Root mean square
RoCoF	Rate of change of frequency
RTE	Le Résea de Transport d'Electricité
RTO	Regional transmission organization
SCADA	Supervisory control and data acquisition
S-N	Stress vs. number of cycles
SPP	Southwest Power Pool
SSCI	Subsynchronous and supersynchronous control interaction
SSR	Subsynchronous resonance
SSTI	Subsynchronous torsional interactions
STATCOM	Static synchronous compensator
VRT	Voltage ride-through

Executive Summary



Historically, electricity system planning criteria and associated performance requirements for interconnecting loads have been grounded in predictable, stable, and manageable load behaviors. Today, the incorporation of new types of large loads, particularly facilities with high proportions of power electronics, such as data centers and crypto mining facilities, introduces new high-impact behaviors to the power system. Unlike traditional industrial consumers, these new loads feature high power densities and rapid power fluctuations, as well as the extensive use of power electronics that impact thermal loadings, voltage levels, voltage stability, transient stability, frequency stability, inter-area oscillations, and subsynchronous oscillations. Such stress on transmission infrastructure can adversely impact power system reliability.

Interconnection requirements for large loads are critical for ensuring reliable grid operation, particularly when these loads are concentrated in specific pockets of the grid. Given the pace and scale of interconnection requests, the frequency and impacts of large load disturbance events are expected to increase. As such, there is urgency to improve and make transparent interconnection requirements for large loads to avoid adverse impacts on grid reliability in the future, as well as costly and technically challenging application of requirements retroactively, as the industry experienced with early wind and solar resources. Transparent, updated interconnection processes are emerging in states with significant large load growth.

Many of the emerging issues for new large loads are similar to issues that arose with inverter-based resources such as solar and wind plants. Utilities and regional grid operators can build on this experience to implement technical performance requirements and standards to effectively govern interconnection of new large loads to safeguard system reliability.

Solutions can be found at the intersection of grid improvements, incentive-based performance specifications for large loads (or other means, such as speed to connection) that take into account loads' capabilities, and operational

Many of the emerging issues for new large loads are similar to issues that have arisen with inverter-based resources. Utilities and regional grid operators can build on this experience to implement technical performance requirements and standards to effectively govern interconnection of new large loads to safeguard system reliability.

practices designed to address the reliability impacts of large loads on the grid. The cost impact for other grid customers also needs to be considered when assessing the trade-offs associated with using grid-side solutions to mitigate reliability impacts of large loads—for example, installing additional transmission assets, procuring additional reserves, or introducing additional ancillary services products.

To address these important issues, the ESIG Large Loads Task Force's project team on large load interconnection requirements established an understanding of large load behaviors, capabilities, and limitations; translated those findings into impacts on the power system; detailed recent power system disturbance events related to large loads; surveyed international interconnection requirements, grid codes, and standards for large load–related requirements; and developed recommendations for a minimum set of requirements for large load facilities.

For this report, the project team reviewed performance requirements in regions that are already experiencing a rapid uptake in large loads and are taking proactive steps to specify performance requirements at loads' point of interconnection. These requirements are often developed through comprehensive stakeholder processes and are based on grid-specific reliability needs and criteria, characteristics, and system protection approaches, while considering capabilities and limitations of large load technologies to conform with the requirements. The report aims to capture the important reliability considerations and criteria that inform the development of each aspect of large load interconnection requirements.

In addition to prevailing requirements and standards established for power quality, the recommended requirements articulated in this report build on detailed information included in the other three reports in this four-report set: *Large Loads: Behaviors, Capabilities, and Limitations* (outlining the ability of large loads to adhere to the requirements to facilitate adoption of the present report's recommendations), *Reliability Impacts of Large, Power Electronics–Interfaced Loads*, and *Large Load Disturbance Events.*

Analysis

The ESIG Large Loads Task Force's investigation of large load characteristics and associated power system impacts identified reliability focus areas which informed the requirements analysis in this report:

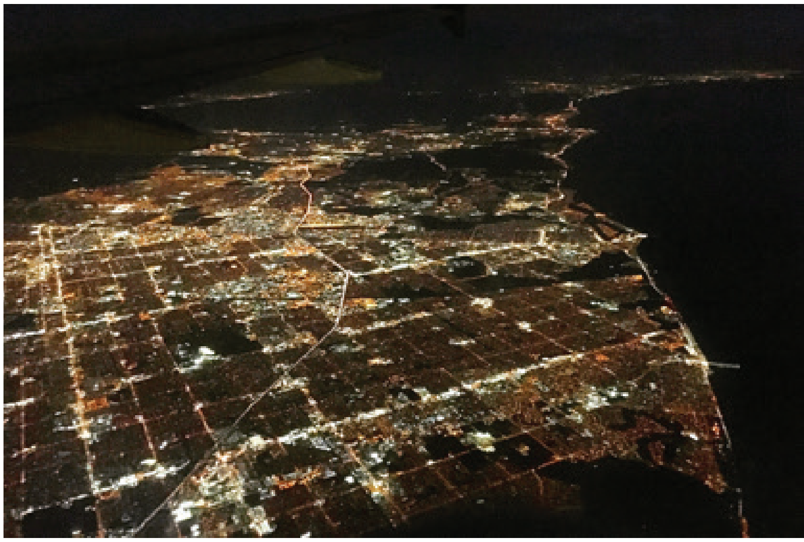
- **Voltage ride-through**: a facility's ability to remain connected to the power system during and following a disturbance
- **Multiple disturbance ride-through**: large load facility designs that incorporate a disturbance counter, after which the large load would be switched to back-up supply or be disconnected
- **Active power recovery**: the post-fault recovery of load that was permitted to reduce during and immediately following a disturbance to facilitate voltage ride-through at a large load facility
- **Frequency ride-through**: a large load facility's ability to remain connected to the power system during high- and low-frequency excursions following a grid disturbance
- **Ramp rates, variability, and cycling**: large loads' potential to exhibit fast, large, and cyclical load changes, which can introduce frequency stability, voltage control, inter-area, and high frequency oscillation–related challenges
- **Reactive power**: the magnitude and control mode for large load reactive power consumption
- **Voltage phase jump**: the ability of a facility to withstand sudden changes in phase following switching operations or disturbances

For each of these areas, the report provides background on associated reliability concerns, an approach to developing performance criteria, a review of applicable established or draft standards, requirement recommendations, and potential approaches that large loads can employ to conform with the requirements when applicable.

- **Monitoring**: the required visibility into the operation of a large load facility considering data fidelity, resolution, and access
- **Modeling**: the appropriate characterization of large load facilities based on the study type

For each of these areas, the report provides background on associated reliability concerns, an approach to developing performance criteria, a review of applicable established or draft standards, requirement recommendations, and potential approaches that large loads can employ to conform with the requirements when applicable.

Findings



By incorporating updated performance requirements in response to new load behaviors on the power system, utilities and regional system operators can support the integration of large loads while also safeguarding the reliability of the power system.

The ongoing dialogue between the power system industry and emerging large load industries like artificial intelligence and crypto mining provides a mutual understanding of behaviors, capabilities, limitations, and needs. These exchanges have led to purposeful technological advancements in facility design which will support large loads' meeting recommended performance requirements.

Table ES-1 provides a summary of the recommended interconnection performance requirements in this report.

TABLE ES-1

Recommended Performance Requirements for Large Load Interconnection

Category	Recommendation
Voltage ride-through	Regional transmission organizations (RTOs), independent system operators (ISOs), and utilities can develop voltage ride-through curves for high- and low-voltage conditions based on local, delayed, and remote fault-clearing times on a given part of the power system; respected contingency events; active power recovery timing; and automated post-contingency actions.
Multi-disturbance ride-through	Large load owners can exclude or disable disturbance counter–based grid disconnection protections in designs. If they are interested in including disturbance-counter logic in their protection designs, they can set the counter threshold to cover multiple events or reclosure operations, with agreement of the transmission owner/operator.
Active power recovery	RTOs, ISOs, and utilities can establish active power recovery criteria considering an appropriate system voltage and configurable recovery timing based on system strength. For example, large loads could be required to reach at least 90% of their pre-fault levels when post-fault voltage levels reach 0.9 pu within a default of 1 s or a specified timing based on system capability.
Frequency ride-through	RTOs, ISOs, and utilities can adopt IEEE 2800 and NERC PRC-029 requirements for inverter-based resources related to frequency ride-through and rate of change of frequency (RoCoF) tolerance as minimum standards for large loads. This will ensure consistent performance and continued coordinated system responses to frequency excursions, which are interconnection-wide phenomena.

(CONTINUED)

TABLE ES-1 (CONTINUED)

Recommended Performance Requirements for Large Load Interconnection

Category	Recommendation	
Ramp rates and variability	**Minute-to-minute and non-cyclical second-to-second variability**	RTOs, ISOs, balancing area authorities, and utilities can examine broader load-following, frequency regulation, and voltage control capabilities when establishing ramp rate criteria. The collective effect of large load variability can be significantly higher than individual facilities, and a continuous system-wide evaluation is required to ensure that reliability is maintained.
	High-frequency cycling	RTOs, ISOs, and utilities can prohibit large loads from introducing forced oscillations into the power system and encourage large loads to leverage solutions to smooth oscillatory behavior at the facility level. If there is residual high-frequency cycling behavior that cannot be mitigated, or if the regional system operator and utility accept high-frequency cycling, they can establish requirements to prevent the introduction of forced oscillations at frequencies and amplitudes of concern for subsynchronous phenomena.
	Low-frequency cycling	RTOs, ISOs, and utilities can prohibit large loads from introducing forced oscillations into the power system and encourage large loads to leverage solutions to smooth oscillatory behavior at the facility level. If there is residual low-frequency cycling behavior that cannot be mitigated, or if the regional system operator and utility accept low-frequency cycling, they can establish requirements to prevent the introduction of forced oscillations at frequencies and amplitudes of concern for major known interconnection inter-area modes. Natural oscillatory modes are related to physical characteristics of the power system, which continues to undergo significant changes. Changes to existing known modes and introduction of new modes may occur. Regional system operators and utilities can maintain authority to update these modes of concern as their systems evolve.
Reactive power capability	Utilities can continue their established approaches to connection requirements related to reactive power capability, which inherently inform voltage control requirements and operating philosophies. A study-based approach can be used to determine when control modes need to be adjustable from power factor control to Q control mode and voltage control mode.	
Voltage phase-jump withstand	RTOs, ISO, and utilities can perform an initial analysis to identify the maximum phase jump on their system for recognized planning and operational events. If the observed phase jumps exceed the ± 25 degrees established by IEEE and NERC for inverter-based resources, a jurisdictional-specific requirement can be implemented. Otherwise, the IEEE and NERC requirement for inverter-based resources can serve as a standard for large loads.	
Monitoring	Large load owners can install monitoring devices that can stream and record high-fidelity data and will need to maintain recorded data for at least 20 days, consistent with NERC PRC-028 requirements for inverter-based resources. The sample rates must respect the Nyquist rate. Given the potential for high-frequency oscillations, a minimum sampling rate of 100 Hz should be applied.	
Modeling	RTOs, ISOs, and utilities can require large load facilities to provide appropriate static, positive-sequence phasor-domain dynamic, harmonic, and electromagnetic transient models, along with accompanying high-resolution load profiles. There is limited availability of mature generic library models, insufficient data for model development and parameterization, a lack of standard submission requirements, and missing validation protocols. Industry can adopt the following steps to enhance current modeling practices: • Develop standardized modeling requirements • Develop generic library models suitable for bulk system reliability studies • Implement model validation frameworks • Enhance industry collaboration • Integrate modeling into interconnection processes	

Source: Energy Systems Integration Group.

Introduction

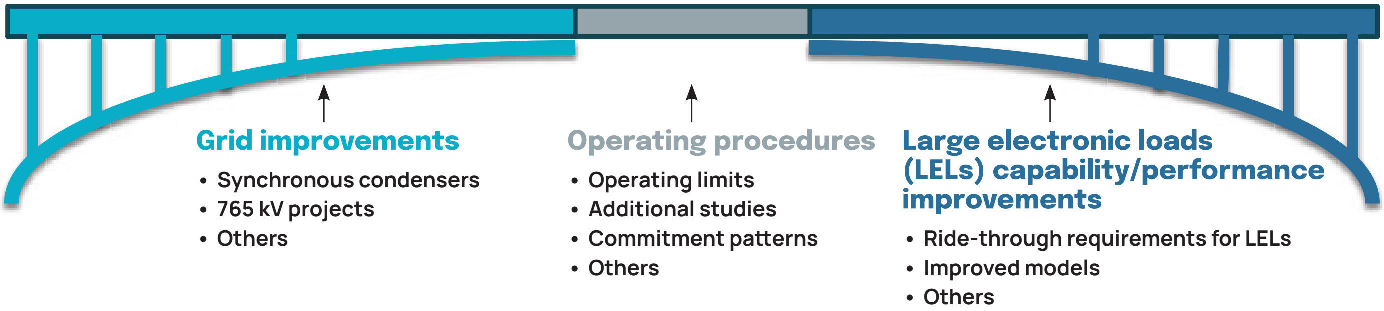
Prevailing power system planning practices and load interconnection requirements were developed considering predictable demand and incremental increases in load. But today there is unprecedented interest in connecting new large loads with high electronic composition, such as data centers and crypto mining facilities. These load facilities can demand 10s of megawatts to more than 1,000 MW and introduce new operating characteristics, including rapid and potentially cyclical fluctuations in demand and voltage ride-through limitations. These characteristics can stress the transmission system and lead to reliability concerns by impacting thermal loadings of transmission lines, voltage levels, voltage stability, transient stability, frequency stability, inter-area oscillations, and subsynchronous oscillations.

It is critical to develop and implement technical performance requirements and standards for these new types of large loads, given the pace and scale of connection requests and approvals, the increasing frequency and impacts of large load disturbance events, and the potential reliability impacts if new large load behaviors are left unmitigated. In developing new large load performance requirements, the industry can leverage its experience and lessons learned in developing these requirements for inverter-based resources (IBRs), such as solar and wind plants, in recent years.

As utilities, independent system operators (ISOs), and regional transmission organizations (RTOs) develop technical performance requirements to mitigate new large load behaviors that pose reliability risks, they can consider the capability of these facilities to fulfill potential incentive-based performance obligations (Figure 1, right side) and the need for grid improvements (Figure 1, left side). Examples of grid improvements include installing

FIGURE 1

Bridging the Grid Improvements and the Requirements for Large Load Capability and Performance



As utilities, independent system operators (ISOs), and regional transmission organizations (RTOs) develop technical performance requirements to mitigate new large load behaviors that pose reliability risks, they need to consider the capability of these facilities to fulfill potential incentive-based performance obligations (right side) and the need for grid improvements (left side), and how the two sides can be bridged by implementing new operational practices aimed at addressing the reliability impacts of large loads on the grid.

Source: Electric Reliability Council of Texas, Large Load Workshop, June 2025, https://www.ercot.com/calendar/06132025-Large-Load-Workshop.

additional transmission assets, procuring additional reserves, and introducing new ancillary services products. Grid operators can also consider how to bridge large load capabilities and grid needs by implementing new operational practices aimed at addressing large load reliability impacts. When considering grid solutions, the cost implications for other grid customers and potential trade-offs need to be carefully examined.

The Project Team's Approach

The ESIG Large Loads Task Force's Interconnection Performance Requirements Project Team used the North American Reliability Corporation's (NERC's) definition of a large load as "any commercial or industrial individual load facility or aggregation of load facilities at a single site behind one or more point(s) of interconnection that can pose reliability risks to the bulk power system due to its demand, operational characteristics, or other factors. Examples include, but are not limited to, data centers, cryptocurrency mining facilities, hydrogen electrolyzers, manufacturing facilities, and arc furnaces."[1] The main tasks of the project team were to:

- Establish an understanding of large load behaviors, capabilities, and limitations
- Translate those findings into impacts on the power system
- Detail recent power system disturbance events related to large loads
- Survey international interconnection requirements, grid codes, and standards for large load–related requirements
- Develop recommendations for a minimum set of performance requirements for large load facilities

The project team's findings are presented in four reports:

- *Large Load Performance Requirements: Current Practices and Recommendations* (this report)
- *Large Loads: Behaviors, Capabilities, and Limitations*
- *Reliability Impacts of Large, Power Electronics–Interfaced Loads*
- *Large Load Disturbance Events*

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[1] NERC Large Loads Task Force White Paper, "Characteristics and Risks of Emerging Large Loads," July 2025, https://www.nerc.com/globalassets/who-we-are/standing-committees/rstc/whitepaper-characteristics-and-risks-of-emerging-large-loads.pdf.

The recommended requirements articulated in this report build on the detailed information gathered for the other three reports, along with prevailing requirements and standards established for power quality. The recommendations also consider established or draft requirements for large load interconnection across ISOs, RTOs, other transmission system operators, and utilities in the U.S., Europe, and Canada (Table 1, p. 4).

These regions are already experiencing a rapid uptake in new large loads and are taking proactive steps to specify performance requirements at the point of interconnection (POI) of a large load facility. These requirements are often developed through comprehensive stakeholder processes and are based on each grid's reliability needs, criteria, characteristics, and system protection approaches, while considering capabilities and limitations of large load technologies to conform with the requirements. The Large Loads Interconnection Performance Requirements Project Team strove to capture the important reliability considerations and criteria that inform the development of each specific aspect of large load interconnection requirements, giving strong consideration to the ability of large loads to adhere to the requirements in order to facilitate adoption.

Large Load Performance Requirements

Each of the following sections provides: (1) background on a particular reliability concern and criteria that serve as the basis for each requirement, (2) an approach to developing performance criteria, (3) a review of applicable established or draft standards, and (4) requirement recommendations and potential approaches that large loads can employ to conform with the requirements.

While the focus of the work was primarily on large loads, they are increasingly being paired with on-site generation, and ambiguity exists regarding performance requirements that should be applied to such generation. For paired load + on-site generation, the performance issues and requirements reviewed in this report could be considered as net at the POI if load and generation will not operate independently. If load or generation is intended to operate while the other is unavailable, the performance for each can be measured at the generation or load facility level. For load + generation participation models that do not share a common POI, performance for each facility would be measured at its respective POI.

The following sections provide context and frameworks for regional grid operators and utilities as they determine requirements that safeguard the reliability of the power system and provide visibility to large loads on drivers and implementation approaches.

The report provides context and frameworks for regional grid operators and utilities as they determine requirements that safeguard the reliability of the power system and provide visibility to large loads on drivers and implementation approaches.

TABLE 1

Established or Draft System Operator Requirements Reviewed for This Report

System Operator	Location	Requirements and Standards
Alberta Electric System Operator (AESO)	Canada	Alberta Electric System Operator, "AESO Connection Requirements for Transmission-Connected Data Centres," Draft for Stakeholder Review, August 22, 2025, https://aesoengage.aeso.ca/49634/widgets/209340/documents/157140. Section 503.15 of the ISO rules, https://www.aeso.ca/rules-standards-and-tariff/iso-rules/section-503-15-interconnected-electric-system-protection/.
American Transmission Company (ATC)	U.S.	ATC, "Load Interconnection Guide, V. 15," August 22, 2025, https://www.atcllc.com/wp-content/uploads/Load-Interconnection-Guide_Rev-15_Final_082225.pdf ATC, "Transmission Planning Criteria, V. 25," August 28, 2025, https://cdn.misoenergy.org/ATC%20TO%20Planning%20Criteria108210.pdf?_t_id=cLeRKiD2xK6n-VlclgVPqA%3d%3d&_t_uuid=eFSbAnVjRXSJZ5qhvRHV9g&_t_q=local+planning+criteria+ATC&_t_tags=language%3aen%2csiteid%3a11c11b3a-39b8-4096-a233-c7daca09d9bf%2candquerymatch&_t_hit.id=Optics_Models_Find_RemoteHostedContentItem/108210&_t_hit.pos=3.
EirGrid	Ireland	EirGrid, "Functional Specification: 110/220/400 kV Control, Protection and Metering," December 22, 2020, https://cms.eirgrid.ie/sites/default/files/publications/Control-Protection-and-Metering-Functional-Specification.pdf.
Electric Reliability Council of Texas (ERCOT)	U.S.	P. Gravois, "ERCOT Large Electronic Load Voltage Ride-Through Performance Requirements (Proposal)," November 20, 2025, Electric Reliability Council of Texas. Internal presentation to the ERCOT Large Load Working Group. Electric Reliability Council of Texas, "Requirement for Disturbance Monitoring Equipment Installation and Configuration for Large Loads," https://www.ercot.com/services/comm/mkt_notices/M-A050925-01. Electric Reliability Council of Texas, "Nodal Operating Guide Section 6," https://www.ercot.com/mktrules/guides/noperating/current.
Energinet	Denmark	Energinet, "Technical Regulation 3.4.3–Requirements for Transmission-Connected Demand Facilities, Revision 1. Doc. 24/06143-12," Effective beginning November 1, 2024 (Fredericia, Denmark), https://en.energinet.dk/media/ep3ofgzp/17_07437-64-dcc-appendix-1d-simulation-model-approved.pdf.
Fingrid	Finland	"KJV2026—New Requirements for Demand Connections: What, Why and When?" Stakeholder presentation, June 5, 2025, https://www.fingrid.fi/globalassets/dokumentit/fi/palvelut/kulutuksen-ja-tuotannon-liittaminen-kantaverkkoon/2025-06-05-kjv2026-main-requirements-draft-for-stakeholders.pdf.
Independent Electricity System Operator (Ontario) (IESO)	Canada	Independent Electricity System Operator, "Chapter 4: Grid Connection Requirements—Appendices," Rul-12, Renewed Market Rules, December 3, 2025, https://www.ieso.ca/-/media/Files/IESO/Document-Library/Renewed-Market-Rules-and-Manuals/market-rules/ieso-mr-chapter0-4-appx.pdf.
Le Résea de Transport d'Electricité (RTE)	France	RTE, "Article 8.3.5—Cahier des Charges des Capacités Constructives d'une Installation de Consommation. Documentation Technique de Référence, Version 1.0" (2024), https://www.services-rte.com/files/live/sites/services-rte/files/documentsLibrary/Article_8.3.5__CdC_des_capacites_constructive_d_une_installation_de_consommateurs_1897_f.r
Southwest Power Pool (SPP)	U.S.	Southwest Power Pool, "High-Impact Large Load Ride-Through Requirements," SPP Operations and Planning, Policy and Research Team, ver. 0.1, July 2025, https://www.spp.org/documents/74635/spp%20hill%20fault%20ride%20through%20requirements-v1.0-8-19-2025%20%28updated%20version%29.docx.
TenneT	Germany	"Anhang Netzanschlussregeln—System Needs and Functions, Annex E.300: Requirements for Power to Gas Demand Units," Rev. 1.2, Bayreuth, Germany, April 2024, https://tennet-drupal.s3.eu-central-1.amazonaws.com/default/2024-04/Anhang_E_Power_to_Gas_Demand_Units.zip.

Source: Energy Systems Integration Group.

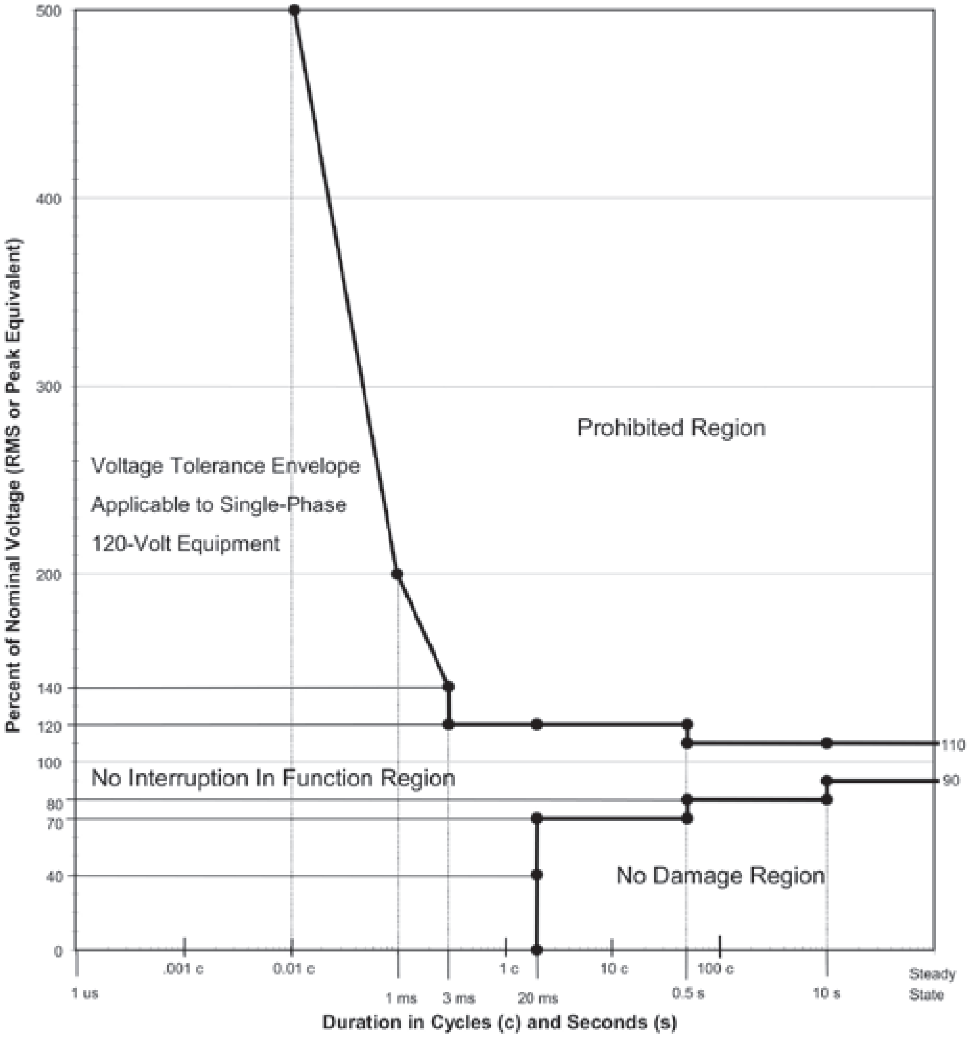
Voltage Ride-Through

Voltage ride-through (VRT) capability of large loads is viewed by utilities and system operators globally as one of the most important aspects of power system reliability. VRT is a facility's ability to remain connected to the power system during and following a disturbance. Facilities' inability to ride through routine contingency events could result in frequency excursions; high-voltage conditions; thermal overloads; cascading outages of generation, load, and other equipment; transient instability and/or voltage collapse; and, potentially, system-wide blackout. The concern about a lack of VRT capability from large loads is emerging primarily due to their size and high geographical concentrations.

Currently, voltage ride-through considerations for large load equipment are focused on guiding a large load facility's design to serve its internal reliability needs (i.e., reliability needs to support the facility's process load). For example, for computing equipment within large load facilities, the Information Technology Industry Council (ITIC) ride-through curve is normally applied to protect voltage-sensitive equipment within a large load facility during voltage disturbances on the grid (Figure 2, p. 6). The ITIC curve is not, however, intended to maximize the ability of large load facilities to remain grid-connected during grid disturbances. As a consequence of this focus on internal reliability needs, large loads' voltage ride-through capability may not be sufficient to ensure grid reliability, as voltage tolerances are misaligned with expected power system disturbance profiles and timing. Dedicated large load VRT curves, focusing on the grid's reliability needs, are necessary to ensure that connecting facilities are able to ride through faults on the power system.

FIGURE 2

ITIC Voltage Ride-Through Curve



In the event that power system voltages fall outside the ITIC curve due to a fault, a large load strictly adhering to the ITIC curve is expected to disconnect from the grid to protect its equipment. For example, in the ITIC curve, voltages below 70% are only tolerated for 20 ms, whereas normal clearing times for faults on the transmission system could be between 80 and 250 ms with associated voltages that are near zero. In such a situation, compliance with the ITIC curve would not drive sufficient VRT capability for a large load facility and thus does not safeguard the reliability of the power system.

Source: Information Technology Industry Council (ITIC).

Developing dedicated large load VRT curves is necessary to support the reliable planning and operation of the power system.

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Developing Voltage Ride-Through Curves

VRT curves specify the voltage-time profiles that facilities must tolerate without disconnecting from the transmission system and generally encompass both under-voltage and over-voltage conditions. Low-voltage ride-through (LVRT) curves identify the required ability for large loads to remain connected during and following disturbances when voltages are depressed, and high-voltage ride-through (HVRT) curves establish expectations for high-voltage conditions.

Low-Voltage Ride-Through Curves

LVRT curves are directly related to local, delayed, and remote fault-clearing times on a given part of the power system, considered contingency events, and automated post-contingency actions. As such, their development requires an understanding of prevailing planning and operating criteria, protection coordination, fault-clearing device specifications, and automated post-contingency actions.

The timings in Table 2 for fault clearing, active power recovery, and automatic actions for considered contingency events illustrate the development of a simplified curve for large loads. The timings leveraged are meant to help explain the development of a VRT curve, and detailed analysis of timing elements would be required by utilities when developing their own VRT curves. Active power recovery, discussed below, is related to the recovery of load that was permitted to reduce during and immediately following a disturbance. Automatic actions for large loads could include, but are not limited to, automatic reactive power device-switching, triggering remedial action schemes, and activation of under-voltage load shedding schemes.

From this information, transmission owners and operators can build an LVRT curve that ensures that large load facilities remain connected for recognized system contingencies. An illustrative curve derived from Table 2 is given in Figure 3 (p. 8).

High-Voltage Ride-Through Curves

A similar approach can be applied for contingencies resulting in high-voltage conditions. If large load facilities do not have HVRT capability, they could be disconnected following contingencies that lead to high-voltage conditions and thus exacerbate these conditions. Such contingencies include loss of load, trip of reactive compensation devices, generation facilities managing high voltages, and the loss of transmission elements that results in reduced flow across a part of the system. If large loads are permitted to reduce their consumption during high-voltage events, the period of high voltage

TABLE 2

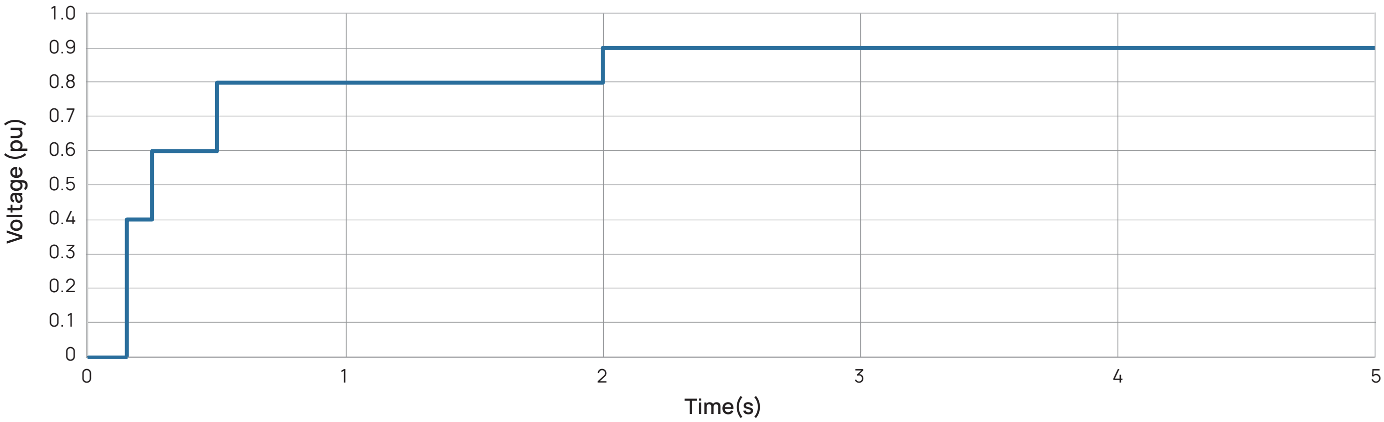
Illustrative Fault-Clearing and Action Times for LVRT Curve Development for Large Loads

Grid Status	Clearing or Action Time	Minimum RMS Voltage
Three-phase permanent fault	0.15 s	0 pu
Single line to ground fault + breaker failure	0.25 s	0.4 pu
Single line to ground fault + remote clearing	0.5 s	0.6 pu
No fault—active power recovery and automatic action time frame	2 s	0.8 pu
No fault—normal operations	Continuous	0.9 pu

Source: Energy Systems Integration Group.

FIGURE 3

Illustrative LVRT Curve Based on Fault-Clearing and Action Times



Source: Energy Systems Integration Group.

could be prolonged until loads restore and system transients attenuate.

Periods of high voltage are already typically 1 to 2 seconds in duration, as this is the time frame within which automatic controls at the system level—such as reactor switching—typically operate to bring voltages back within a normal range. If additional large load facilities trip under these circumstances, this could exacerbate high-voltage issues and cause other facilities to begin tripping on established over-voltage thresholds. Therefore, the establishment of HVRT curves needs to be coordinated with large load ride-through philosophies, automatic reactive switching times, and protection operating times.

To illustrate the development of a simplified curve, Table 3 gives timings for fault clearing, active power recovery, and automatic actions for considered contingency events. The timings included are meant to help explain the development of an HVRT curve; detailed analysis of timing elements would be required by utilities when developing their own HVRT curves.

From this information, transmission owners and operators can build a HVRT curve that ensures that large load facilities remain connected based on routine system contingencies. An illustrative curve is shown in Figure 4 (p. 9).

TABLE 3

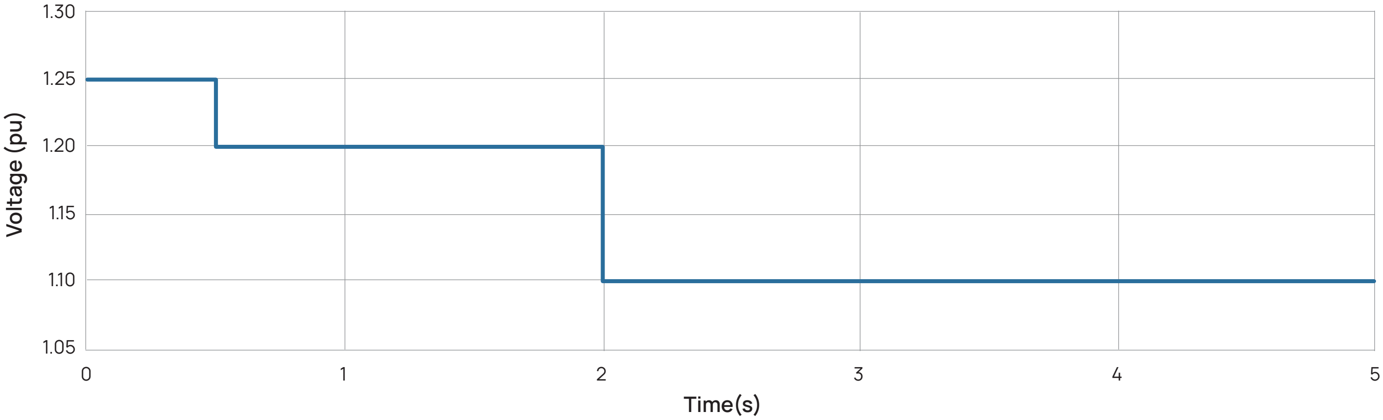
Illustrative Fault-Clearing and Action Times for HVRT Curve Development for Large Loads

Grid Status	Clearing or Action Time	Maximum RMS Voltage
Loss of load, reactive device, or generation facility + load reduction	0.15 s	1.25 pu
Immediately post-fault, load restoration at 50% by 0.5 s	0.15–0.5 s	1.25 pu
Load restoration @ 100%	0.5–1 s	1.20 pu
Automatic reactor switching	2 s	1.1 pu
No fault—normal operations	Continuous	1.1 pu

Source: Energy Systems Integration Group.

FIGURE 4

Illustrative HVRT Curve Based on Fault-Clearing and Action Times



Source: Energy Systems Integration Group.

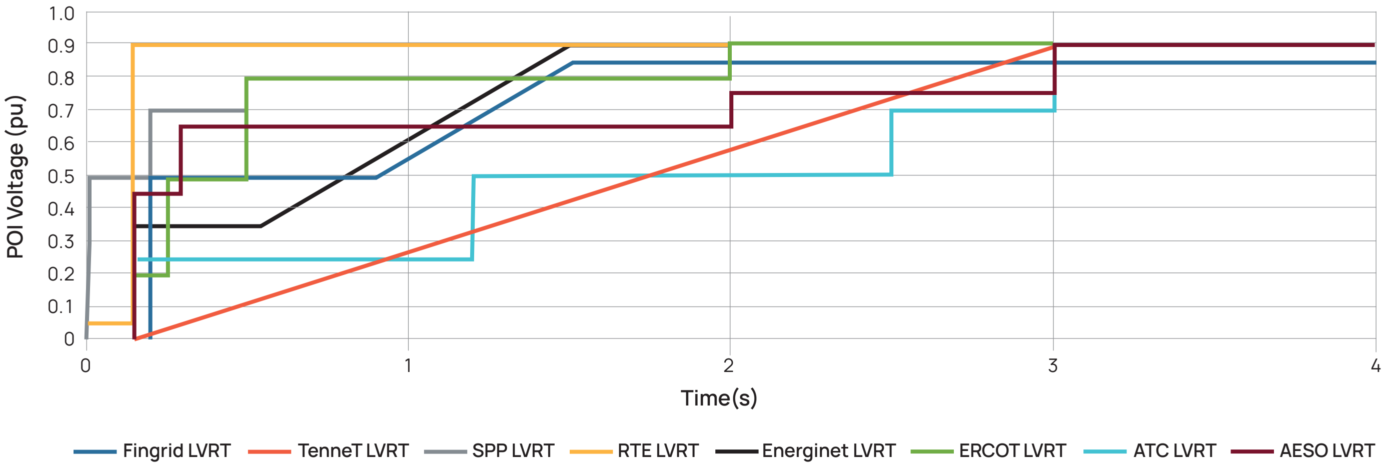
Review of Voltage Ride-Through Requirements

The VRT requirements reviewed by the project team are applicable at the POI and demonstrate varying requirements for VRT, reflecting different grid characteristics, reliability criteria, and system protection philosophies, as summarized in Table 4 (p. 10). The requirements include allowance for current blocking and current limitation at large load facilities—large loads may temporarily reduce their load to facilitate meeting the ride-through criteria. Current limitation involves restricting the current consumed at the large load facility to a value relative to its normal levels (e.g., 125%), while current blocking entails transferring load to back-up power.

The voltage profiles of the reviewed standards are shown in Figures 5 and 6 (p. 11).

FIGURE 5

Comparison of Voltage Ride-Through Requirements: Low VRT Profiles



Notes: AESO = Alberta Electric System Operator; ATC = American Transmission Company; ERCOT = Electric Reliability Council of Texas; LVRT = Low-voltage ride-through; RTE = Le Résea de Transport d'Electricité; SPP = Southwest Power Pool.

Source: Energy Systems Integration Group.

TABLE 4

Comparison of POI Voltage Ride-Through Requirements for Large Loads

Transmission System Operator / Independent System Operator / Transmission Owner	Point of Interconnection Voltage Ride-Through Requirements			
	Low-Voltage Ride-Through (LVRT)	High-Voltage Ride-Through (HVRT)	Current Blocking Mode	Current Limitation Mode
Fingrid	Yes	Yes	Allowed for V < 50%	Allowed for V < 90%
TenneT	Yes	Yes	Allowed for V < 50%	Allowed for V < 90%
Energinet	Yes	No	Allowed for LVRT events; V threshold not specified	Not specified
Le Résea de Transport d'Electricité (RTE)	Yes	Yes	Not specified	Not specified
Southwest Power Pool (SPP)	Yes	Yes	Allowed for LVRT events; V threshold not specified	Allowed, but V threshold not specified
Ontario Independent Electricity System Operator (IESO)	Not detailed*	Not detailed*	Not specified	Not specified
American Transmission Company (ATC)	Yes	Yes	Not specified	Not specified
Alberta Electric System Operator (AESO)	Yes	Yes	Not permitted	Not specified
Electric Reliability Council of Texas (ERCOT)	Yes	Yes	Allowed for V < 80%	Allowed for V < 90%

* Note: The standard does not specify a VRT profile; rather, it requires these facilities to ride through routine switching events.

The table compares different approaches to large load ride-through requirements from utilities and system operators in Europe and North America. This includes consideration for low- and high-voltage ride-through requirements as well as load-limiting behavior during disturbances.

Source: Energy Systems Integration Group.

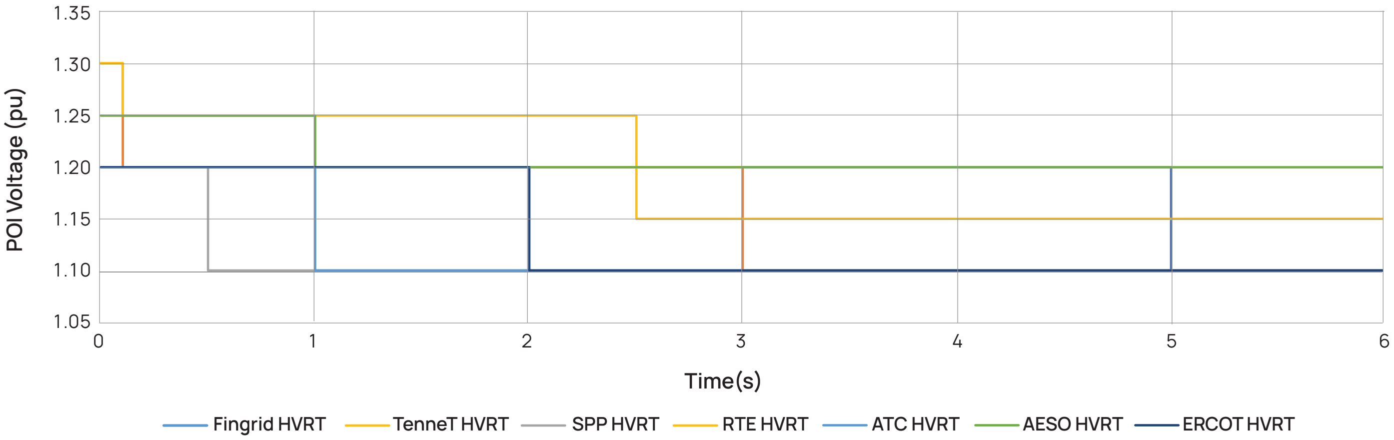
Recommendations for Performance Requirements

System operators and utilities will want to develop voltage ride-through curves for high- and low-voltage conditions based on (1) local, delayed, and remote fault-clearing times on a given part of the power system, (2) respected contingency events, (3) active power recovery timing, and (4) automated post-contingency actions. While different power systems possess unique fault-clearing practices and characteristics that will inform system operators' and utilities' LVRT/HVRT performance requirements, industry alignment could yield benefits by expediting the integration

While different power systems possess unique fault-clearing practices and other characteristics, industry alignment could yield benefits by expediting the integration of large load facilities and reducing equipment costs. For example, implementing a standard similar to IEEE 2800 for large loads would set clear global performance expectations as well as inform minimum acceptable facility designs.

FIGURE 6

Comparison of Voltage Ride-Through Requirements: High VRT Profiles



Notes: AESO = Alberta Electric System Operator; ATC = American Transmission Company; ERCOT = Electric Reliability Council of Texas; LVRT = Low-voltage ride-through; RTE = Le Résea de Transport d'Electricité; SPP = Southwest Power Pool.

Source: Energy Systems Integration Group.

of large load facilities and reducing equipment costs. For example, implementing a standard similar to IEEE 2800 for large loads would set clear global performance expectations as well as inform minimum acceptable facility designs. These minimum performance expectations can then be further adapted to include regional needs.

To support large loads' ability to meet ISO/RTO and utility ride-through requirements, these facilities can leverage devices such as uninterruptible power supplies, rack-level storage, battery energy storage systems (BESS), and E-STATCOMs (enhanced static synchronous compensators) at their facilities. Critical loads can be effectively transferred to back-up power devices while local voltages can be supported by the reactive control devices that control local large load voltage when transmission system voltages are outside normal ranges. However, as noted in the section "Active Power Recovery," load must recover shortly after a fault has cleared to maintain system reliability.

Multiple Disturbance Ride-Through

Current planning and operational practices anticipate the loss of multiple grid elements due to recognized contingency scenarios or to extreme conditions. For example, multiple disturbances could result from the loss of two transmission circuits on a common tower (NERC Category P7 contingency) with differing reclosure times for each, or there could be multiple momentary and permanent faults on different transmission lines during inclement weather, such as a lightning storm.

To protect a facility's equipment, the designs of large load facilities such as data centers incorporate a disturbance counter—for example, three disturbances in one minute (e.g., three strikes rule)—after which the data center would be switched to back-up supply or disconnected from the grid. Similar to the potential impacts of failed ride-through discussed in the previous section, disconnection due to multiple disturbances could result in frequency excursions; high-voltage conditions; thermal overloads; cascading outages of generation, load, and other equipment; transient instability and/or voltage collapse; and potential system-wide blackout.

Review of Multiple Disturbance Ride-Through Requirements

Table 5 includes multi-disturbance-related requirements from organizations in Finland, Germany (TenneT), Canada (Alberta Electric System Operator) and the U.S. (American Transmission Company). Our review of other countries or regions did not identify multiple disturbance requirements.

Recommendations for Performance Requirements

Due to the aforementioned potential reliability impacts, it is recommended that disturbance counter–based grid disconnection protections be excluded in designs or disabled if available.

If large load owners are interested in including disturbance-counter logic in their protection designs, they can set the counter threshold to cover multiple events or reclosure operations, with agreement of the transmission owner or operator.

TABLE 5

Sample Multi-Disturbance Performance Requirements for Large Loads

Transmission System Operator, Independent System Operator, or Transmission Owner	Multiple Disturbance Events
Fingrid	Require large loads to ride-through 10 bolted faults of 100 ms each within a 90 second period
TenneT	Require large loads to ride-through three LVRT events within 30 minutes and five HVRT events within 30 minutes
Alberta Electric System Operator (AESO)	Specify that the minimum ride-through durations are applicable to one or multiple faults in a 10 second window
American Transmission Company (ATC)	Require large loads to sustain three ride-through events over a period of 10 seconds

Source: Energy Systems Integration Group.

Active Power Recovery

Active power recovery (APR) requirements are designed to facilitate load recovery after a disturbance without introducing additional transient stability challenges. In the context of large loads, APR is the post-fault recovery of load that had been permitted to reduce during and immediately following the disturbance. In the absence of APR requirements, load might remain at reduced levels following the disturbance, which could result in frequency excursions; thermal overloads; cascading outages of generation, load, and other equipment; transient instability; and/or voltage collapse. When interconnection performance requirements include APR requirements, post-contingency network conditions can remain as expected while allowing for some load reduction needed to facilitate meeting the ride-through requirements.

Determining Active Power Recovery Criteria

To determine APR criteria—for example, load recovers to 90% of its pre-fault level after 1 second post-fault—one will need to take into consideration actual system voltage recovery after a fault as well as understand the system's ability to stabilize following the load recovery. As such, it is recommended that APR criteria be established considering an appropriate system voltage threshold with the ability to configure recovery timing based on system strength.

In general, if power consumption at a large load facility needs to be reduced to allow for the facility to ride through a routine fault on a transmission system, its resumption of power consumption after the fault is cleared needs to

In general, if power consumption at a large load facility needs to be reduced to allow for the facility to ride-through a routine fault on the transmission system, its resumption of power consumption after the fault is cleared needs to be swift to ensure that the load reduction does not result in any adverse transient stability impacts.

be swift to ensure that the load reduction does not result in any adverse transient stability impacts. Immediate APR may be readily achievable in stronger parts of the power system; however, a slower recovery may be needed to avoid introducing transient stability issues in areas with lower system strength.

Review of Active Power Recovery Requirements

Table 6 lists draft and established APR requirements from multiple jurisdictions. It can be observed that APR requirements are normally designed to restore load as quickly as possible informed by the system's readiness to supply the load, determined in many cases by a system voltage threshold for recovery.

Recommendation for Performance Requirements

APR criteria need to be established for large loads such that they facilitate recovery of load at the earliest opportunity without introducing transient stability challenges. This requires coordination with post-fault system voltage recovery after routine faults as well as an understanding of the system's capability to stabilize following the load recovery. As such, APR criteria can be established considering system voltage and configurable recovery timing based on system strength. For example, large loads could be required to reach at least 90% of their pre-fault levels when post-fault voltage levels reach 0.9 pu within a default of 1 s or a specified timing based on system strength considerations.

TABLE 6

Comparison of Active Power Recovery Requirements for Large Loads

Transmission System Operator, Independent System Operator, or Transmission Owner	Post-Fault Active Power Recovery				
TenneT	Pre-fault active current must be restored after fault clearance.				
American Transmission Company (ATC)	Active power must be fully restored within three cycles after the fault is cleared without shifting to back-up or UPS, otherwise detailed studies are required.				
Energinet	80% of pre-disturbance power must be restored within 5 s (±2% difference allowed).	90% of pre-disturbance power must be restored within 20 s (±2% difference allowed).		95% of pre-disturbance power must be restored within 30 s (±2% difference allowed).	
Fingrid	**Datacenters:** 90% of pre-disturbance power must be restored in ‹0.5 s.	**Electric boilers:** 90% of pre-disturbance power must be restored in ‹1.0 s.	**Power to gas:** 90% of pre-disturbance power must be restored in ‹1.0 s.	**Furnaces:** 90% of pre-disturbance power must be restored in ‹1.0 s.	**Other industry:** 70% of pre-disturbance power must be restored in ‹1.0 s.
Electric Reliability Council of Texas (ERCOT)	≥90% of pre-disturbance power must be restored within 1 s (when V ≥ 0.9 pu).				
Alberta Electric System Operator (AESO)	Default active power recovery time is 1 s, configurable to 10 s depending on system strength.				

Source: Energy Systems Integration Group.

Frequency Ride-Through and Rate of Change of Frequency Withstand

Frequency disturbances result from system-wide imbalances between electricity generation and consumption that can propagate throughout interconnected transmission networks. Unlike voltage disturbances that are typically localized and confined to specific areas, frequency deviations affect the entire synchronous power system and require a coordinated response from all connected facilities to restore balance and stability. Frequency ride-through (FRT) requirements are intended to avoid exacerbating an initial frequency event due to subsequent disconnection of load or generation facilities.

FRT requirements establish the frequency excursion limits and durations that large load facilities must withstand without disconnecting from the transmission system. These requirements address both under-frequency conditions caused by generation-load imbalances and over-frequency conditions resulting from sudden load loss or generation excess. While the disconnection of large loads on under-frequency can potentially help restore the balance between production and consumption and aid frequency restoration, the simultaneous or uncontrolled disconnection of multiple large load facilities may have an undesirable effect on system frequency and lead to a subsequent over-frequency event.

Large frequency events may not only result in large frequency deviations but also be characterized by a high rate of change of frequency (RoCoF)—a fast frequency decline or increase. This typically happens in low-inertia systems and/or during very large generation or load loss. High RoCoF may trigger additional protections on synchronous generators and/or cause malfunction of protective equipment that uses frequency as an input signal.

Frequency deviations affect the entire synchronous power system and require a coordinated response from all connected facilities to restore balance and stability. FRT requirements are intended to avoid exacerbating an initial frequency event due to subsequent disconnection of load or generation facilities.

Determining Frequency-Ride Through and RoCoF Criteria

Under-frequency ride-through requirements are usually established based on expected frequency deviations and their duration after the credible single-largest infeed loss that a power system is expected to withstand without activation of under-frequency load shedding (UFLS). The expected frequency deviations and their duration also take into account the availability and response time of different frequency control measures and under-frequency protection settings of synchronous generators on the system.

In the case of over-frequency events, the primary concern is with cascading tripping of additional synchronous generation on their over-frequency protection. The factors determining largest expected over-frequency are the loss of largest load facility (or exporting high-voltage DC (HVDC) tie-line), availability and response time of the frequency control measures, and over-frequency protection settings of synchronous generators.

Historically, over-frequency was less of a concern because load facilities were relatively small compared to generation facilities. As a result, there may not be sufficient frequency-control measures available to address over-frequency events in a timely manner, compared to under-frequency events which were the focus of frequency control in the past. Furthermore, since the unexpected disconnection of large loads due to lack of FRT capability may exacerbate over-frequency conditions after the initial grid disturbance, the over-frequency part of the FRT requirement calls for careful consideration.

RoCoF criteria are usually based on the loss of the largest generation facility, load facility, or HVDC tie-line that the system is expected to survive without: (1) triggering any other protections (e.g., any RoCoF protections on generators), or (2) resulting in malfunction or misoperation of protective devices.

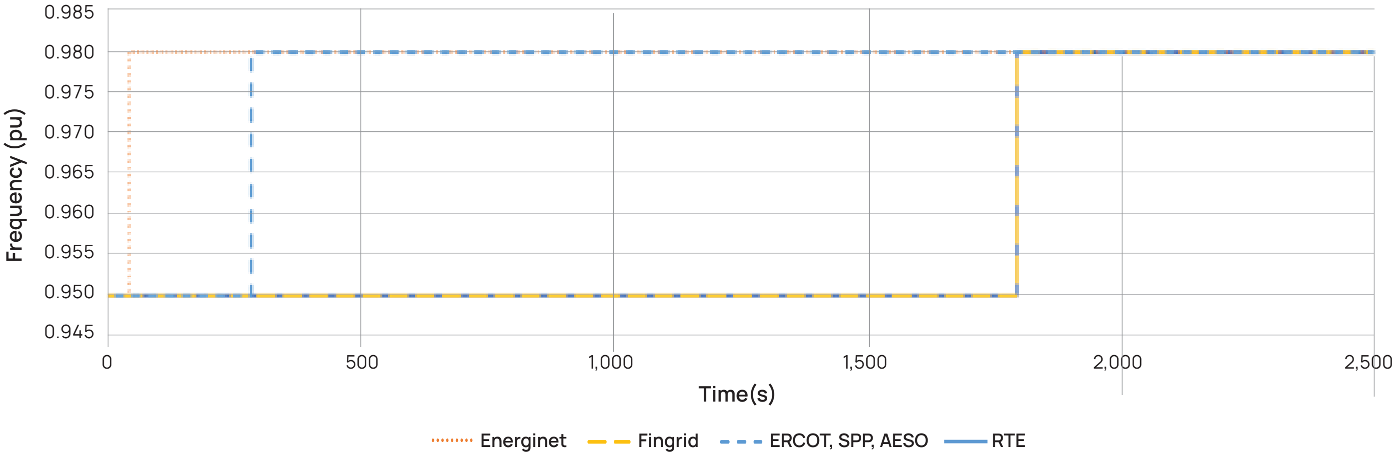
Review of Frequency Ride-Through Requirements

The standards reviewed by the project team establish different frequency ride-through requirements reflecting varying system characteristics and operational philosophies, as depicted in Figures 7 and 8 (p. 17). However, there is close alignment among the North American utilities that implemented FRT requirements for large loads based on requirements established for IBR FRT and RoCoF (5 Hz/s) criteria in IEEE 2800 and NERC PRC-029.

Figures 7 and 8 highlight proposed or established low- and high-frequency ride-through requirements for large

FIGURE 7

Comparison of Frequency Ride-Through Requirements: Low FRT Profiles



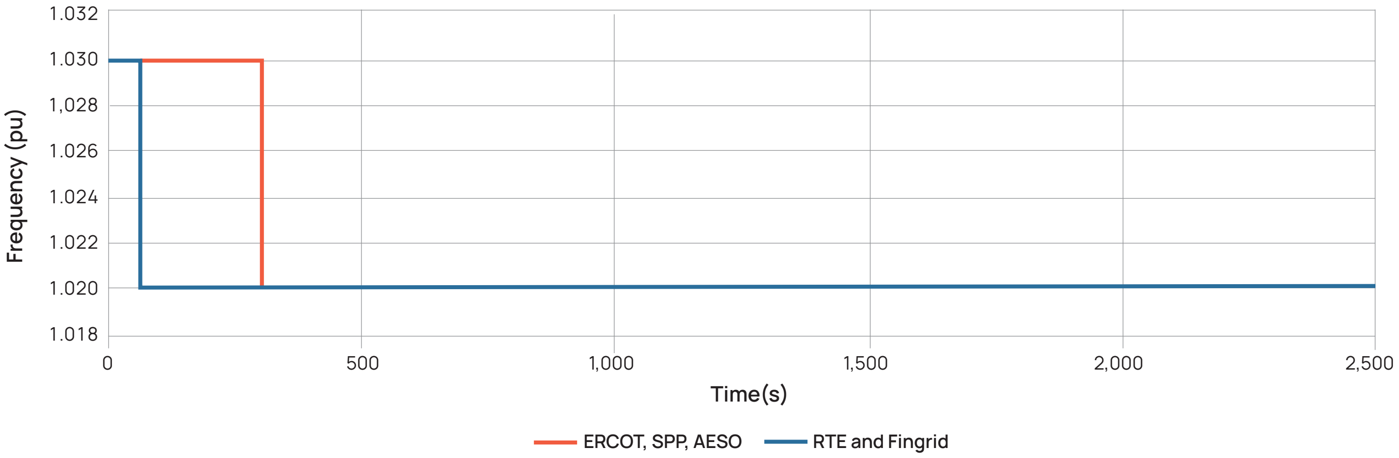
Low-frequency ride-through requirements are usually established based on expected frequency deviations and their duration after the credible single-largest infeed loss that a power system is expected to withstand. North American utilities that have implemented frequency ride-through requirements for large loads have used established standards for inverter-based resources' frequency ride-through.

Note: The RTE (solid blue line) is under the yellow dashed line.

Source: Energy Systems Integration Group.

FIGURE 8

Comparison of Frequency Ride-Through Requirements: High FRT Profiles



High-frequency ride-through requirements are usually established based on expected frequency deviations and their duration after the credible single-largest load facility or exporting high-voltage DC tie-line loss that a power system is expected to withstand. North American utilities that have implemented frequency ride-through requirements for large loads have used established standards for inverter-based resources' frequency ride-through.

Source: Energy Systems Integration Group.

loads across reviewed jurisdictions. In addition to the FRT profiles shown in the figures, most of the standards reviewed also prescribe withstanding frequency gradients (RoCoF) of up to ±2 Hz/s, with the Alberta Electric System Operator targeting 5 Hz/s.

Recommendation for Performance Requirements

The requirements specified in IEEE 2800 and NERC PRC-029 for IBRs' frequency ride-through and RoCoF tolerance should be adopted as minimum standards for large loads as well. This will ensure consistent performance and continued coordinated system responses to frequency excursions, which are interconnection-wide phenomena. The FRT criteria requirements established for IBRs in IEEE 2800 and NERC PRC-029 are shown in Table 7.

TABLE 7

IEEE 2800 and PRC-029 IBR Frequency Ride-Through Criteria

System Frequency (Hz)	Minimum Ride-Through Time (sec)
> 61.8	May trip
> 61.2	299
≤ 61.2 and ≥ 58.8	Continuous
< 58.8	299
< 57.0	May trip

Source: PRC-029-1, North American Electric Reliability Corporation, "Frequency and Voltage Ride-Through Requirements for Inverter-Based Resources," https://www.nerc.com/globalassets/standards/approved-standards/prc/prc-029-1.pdf.

Ramp Rates, Variability, and Cycling

Large loads' processes, such as artificial intelligence (AI) training workloads, include cyclical high-ramping consumption patterns due to graphics processing unit (GPU) transitions between high-power, computation-heavy activity phases and lower-power communication-heavy phases. Large load variability can also introduce frequency control challenges, especially when numerous load facilities are, for example, increasing and decreasing their load by up to 60% of facility rating every few seconds. The reliability of a power system can be negatively impacted by MW/time variability of generation and load in the following time frames:

- **Minute-to-minute:** Variability on a minute-to-minute basis can impact the ability to control area control error (ACE)/frequency regulation, load follow based on online generator ramping capability, and voltage control depending on devices available.
- **Second-to-second:** Variability on a second-to-second basis can also impact the ability to control ACE/frequency regulation, while cycling can result in inter-area oscillations and coordination challenges with slower-acting controls.
- **Intra-second:** Cyclic intra-second variability can introduce forced oscillations at higher frequencies, which can trigger subsynchronous oscillatory phenomena such as subsynchronous control interactions (SSCI) (normally between 5 Hz and 35 Hz, and more prevalent between 5 Hz and 15 Hz) and subsynchronous torsional interactions (SSTI) (normally between 5 Hz and 35 Hz, and more prevalent between 5 Hz and 20 Hz).

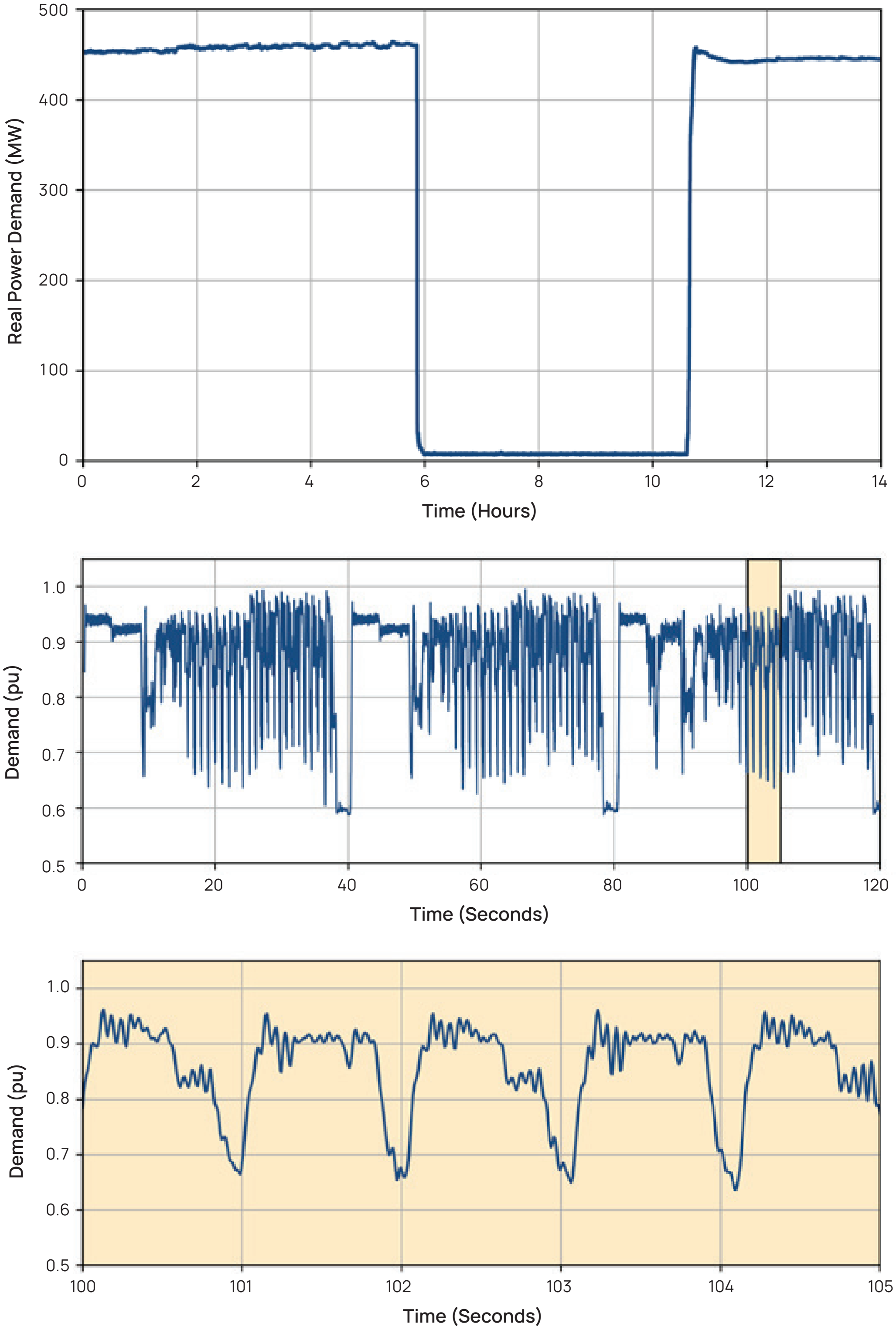
Large load facilities, including facilities with high concentrations of electronics such as data centers and crypto mining facilities, can have very high ramps that allow them to reach peak load from low levels in less than a second, along with load levels ranging from the size of small to medium-sized cities. Due to the nature of their load, the facilities' demand can also be highly variable, often cycling every few seconds. Large load consumption can be segregated into the same three profiles that are of concern for system operators and utilities: minute-to-minute, second-to-second, and intra-second.

The time frames are illustrated in Figure 9 (p. 19), with the first image showing an illustrative hourly profile, the second depicting second-to-second variability, and the third focusing on intra-second variability.

The next subsection provides more detail on the minute-to-minute and non-cyclical second-to-second elements of load profiles, cyclical second-to-second elements, and intra-second elements.

FIGURE 9

Elements of Large Load Consumption Profiles



Source: North American Electric Reliability Corporation, "Characteristics and Risks of Emerging Large Loads," July 2025, https://www.nerc.com/globalassets/who-we-are/standing-committees/rstc/3_doc_white-paper-characteristics-and-risks-of-emerging-large-loads.pdf.

Minute-to-Minute and Non-Cyclical Second-to-Second Variability

Today, non-cyclical second-to-second active power changes related to load and generation variability are managed through frequency regulation practices, including the procurement and scheduling of resources to provide regulation services. Minute-to-minute changes are also addressed by regulation services, and, in addition, their cumulative impact is addressed by real-time generation dispatch at each dispatch interval.

Specifying minute-to-minute active power ramp rate limits is essential to maintain real-time power balance (generation vs. load) and system voltages during normal grid operation. Without these constraints, large loads could rapidly increase or decrease their consumption, potentially causing frequency deviations if generation resources are not able to sufficiently regulate frequency and follow load patterns. While this concern can potentially also be addressed with continuously reassessing and increasing regulation reserves, the trade-off between these two mitigation measures—limiting large load ramp rates versus increasing regulation reserves—has to be evaluated.

The Electric Reliability Council of Texas (ERCOT) has highlighted the impact of large load ramping and variability on the adequate scheduling of ancillary services, including frequency regulation products. ERCOT noted instances in August 2024 when regulation down ancillary service procurement was less than the ramping experienced by largely crypto mining load. This under-scheduling of ancillary services can result in frequency excursions, the need to leverage one-time dispatch instructions, or activation of reserves. As large load integration continues to increase, if ramping behaviors are unmitigated, frequency regulation will become a growing area of concern and risk for balancing authorities.

Those same changes in consumption may impact flows on transmission lines, which could result in rapid changes to the system voltages, especially in weaker parts of the system. This could lead to operations outside normal voltage ranges and instability.

Determining Minute-to-Minute and Non-Cyclical Second-to-Second Ramp Rate Criteria

Multiple factors can influence how ramp rate criteria are established for minute-to-minute and non-cyclical second-to-second changes, and the most limiting of the considerations below will inform the ultimate ramp rate requirement.

The combined impact of large load ramps is an important consideration when establishing ramping criteria, as illustrated by the example detailed above for ERCOT, which experienced ramps exceeding the procured amount of regulation down ancillary service. Balancing authorities must carefully consider the ramping capabilities of their generation, storage, and controllable load[2] resource fleet in response to dispatch instructions, frequency regulation approach and procured capacity, and the total capacity and ramping capability of large loads interconnecting to the system.

To properly ascertain expected capability and needs, a first step is to determine the capacity for generation resources to follow load at dispatch intervals and to regulate frequency between dispatch intervals. This can

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[2] For example, in ERCOT the Controllable Load Resource (CLR) construct was introduced at the end of 2010. CLR is a large electricity consumer that can be dispatched by the grid operator to actively reduce or increase its power consumption in real time to help balance the grid. Unlike other loads, CLRs can respond directly to signals from ERCOT to provide flexibility, contributing to services like frequency regulation and real-time energy market/dispatch participation.

be achieved by (1) conservatively establishing the expected amount of active power headroom normally online and considering associated combined generation, storage, and controllable load resource ramp rates, while (2) reviewing historical frequency regulation usage relative to the quantity scheduled, along with the potential for additional regulation reserve amounts the balancing authority is prepared or able to procure in the future. This information can be compared with expected large load ramps to identify any disparity between ramping needs and ramping capability, which can be addressed by increasing regulation reserves or incorporating ramp-rate limits. The trade-off between these two measures needs to be evaluated both from economic and technical capability perspectives.

With respect to load following from a voltage perspective, it is important to examine the ability of the system to maintain voltages within continuous operation ranges during normal operation. Determining the change in voltage for changes in power consumption at the large load POI can help determine how much the large load's consumption can change without adversely impacting voltage and stability. This can then be compared with the response time of grid-side voltage controls that are in place to manage voltage changes in response to variability. Together, the acceptable change limit and response times can be used to establish an acceptable ramp rate. Additional reactive power compensation may also be required from the large load facility to meet power factor requirements at the POI or from the transmission owner to maintain system voltage when serving the large load. Traditionally, the practice for power factor correction for large loads has been focused on peak load analysis, often requiring static shunt capacitors or reactors. Given the rapid nature of the variability of emerging large loads, static reactive compensation devices may not be appropriate—as they are not designed to switch in quickly and numerous times per day, let alone multiple times per hour—and dynamic reactive compensation devices, such as static VAR compensator (SVC) or STATCOM, will be required either directly at the large load POI or procured locally by transmission owner.

Table 8 lists ramp rate criteria across different jurisdictions, with some specifying specific limits or electing to leverage a study-based approach and others not yet having ramp rate limits in place.

TABLE 8

Active Power Ramp Rate Limits for Large Loads

Transmission System Operator / Independent System Operator / Transmission Owner	Maximum Allowed Active Power Ramp Rate (Up and Down)
Fingrid	Adjustable from 5% to 100% of $P_{max/min}$ but with a maximum of 50 MW/minute
TenneT	Not specified
Energinet	60 MW/minute
Le Résea de Transport d'Electricité (RTE)	Defined on a case-by-case basis
Southwest Power Pool (SPP)	Defined on a case-by-case basis
Ontario Independent Electricity System Operator (IESO)	Not specified
Electric Reliability Council of Texas (ERCOT)	Not specified
American Transmission Company (ATC)	1. Small MW variations: Changes in active power must be less than 25 MW for any period of time less than 5 s 2. Large MW variations: Any change in active power that is greater than 50 MW should be limited to a rate of change less than 0.5 MW/s
Alberta Electric System Operator (AESO)	10 MW/minute

Source: Energy Systems Integration Group.

Recommendations

ISOs/RTOs, balancing authorities, and utilities can examine broader system-wide load-following, frequency regulation, and voltage control capabilities to establish large load ramp rate criteria, as outlined in the previous section. The collective effect of large load variability can be significantly more than that of individual facilities, and a continuous system-wide evaluation is required to ensure reliability is maintained. These analyses can factor in potential increases in frequency regulation service. The results of these analyses can then be used to set ramp rate limit standards (if any) and make decisions on whether to change volumes of procured frequency regulation

reserve. Operability analyses can be incorporated into planning study cycles to allow for the consideration of ramping on the determination of voltage-control devices, which, as previously noted, could necessitate the inclusion of dynamic reactive compensation either from large loads directly at the POI or procured locally by the transmission owner.

High-Frequency Cycling: Torsional and Controller Interactions

Cyclic intra-second active power variability can introduce forced oscillations at higher frequencies (higher than 1 Hz). These can trigger subsynchronous phenomena (such as SSCI) with IBRs and power electronics–based voltage-control devices (normally between 5 Hz and 35 Hz, more prevalent between 5 Hz and 15 Hz) and SSTI (normally between 5 Hz and 35 Hz, more prevalent between 5 Hz and 20 Hz). These interactions can result in voltage swings and torsional vibrations in synchronous machines that can damage equipment or trigger equipment protections.

Determining High-Frequency Cycling Criteria

A survey- and study-based approach is usually leveraged to identify the potential for subsynchronous oscillations. The first step is requesting models of existing and approved facilities in the vicinity of the proposed large load location, such as IBRs, synchronous generators, HVDC, series capacitors, voltage control devices, and other large loads. If detailed site-specific models are not available, models for similar facilities or generic models can be leveraged, although there is the potential for loss of accuracy and reduced dependability of the study results. Next, the large load model and its associated high-resolution intra-second profile are obtained. The load profile can then be broken down to identify the frequencies being injected. If at the time of the analysis a detailed load profile is not available, representative profiles with varying frequency components can be leveraged to cover a range of possible possibilities. A system model including the aforementioned facilities is created in an electromagnetic transient (EMT) study platform, where potential for interactions is analyzed under normal operation and contingency conditions.

One form of interaction is SSTI, where the large load could interact with the long shaft of a synchronous generation unit with one or multiple turbine sections, a generator, and an exciter. These turbines could have natural torsional frequencies that could be excited by high-frequency cycling in large load profiles, resulting in the introduction of damaging shaft vibrations.[3]

In the example in Figure 10 (p. 23), a 900 MVA generation unit with a single turbine, generator, and exciter is modeled in detail to ascertain whether there is potential for interaction

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[3] See https://www.esig.energy/event/lltf-webinar-datacenter-load-impact/.

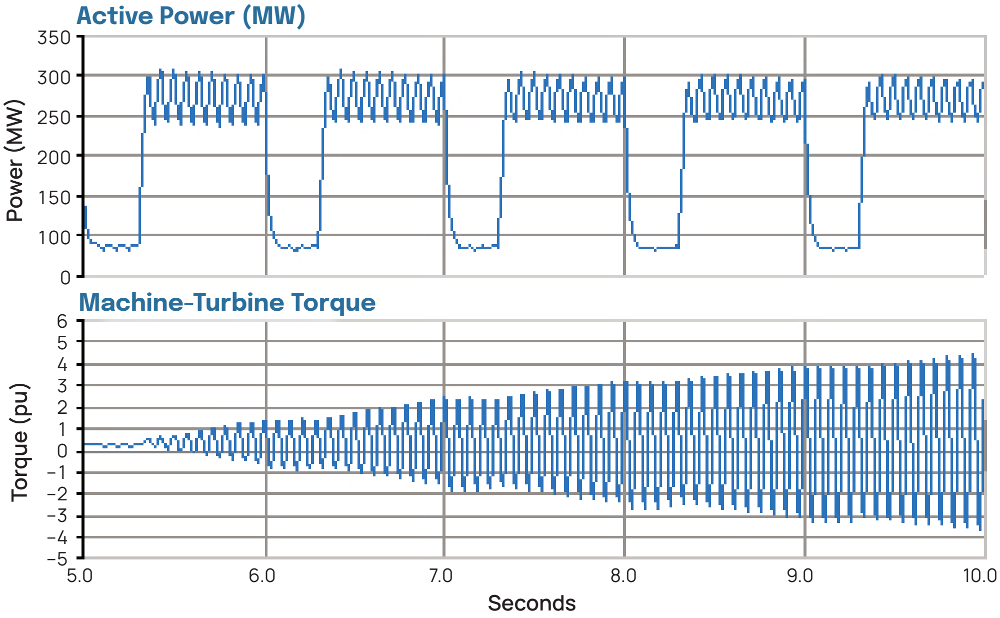
with a new AI data center. The shaft can be accurately represented using a "multi-mass module" in EMT study platforms. In this example, the generator is determined to have a natural frequency of 14 Hz based on data from the generator owner. The AI training process is represented with a power oscillation with an amplitude around 200 MW at 1 Hz and 50 MW at 14 Hz, which results in the torque between the turbine and generator amplifying due to resonance at the shaft's natural frequency of 14 Hz. The figure shows the load profile and the associated SSTI growing to 4 pu torque. This level of interactions could result in shaft fatigue, shaft damage, or tripping of the generator unit through associated protections.

Once the frequencies of concern are identified, they can be communicated back to the large load facility as restricted cycling frequencies in their load profiles. If cycling is inevitable due to the nature of the load, the next step would be to consult the stress vs. number of cycles (S-N) curve for the turbine-generator shaft. These curves show the relationships between torsional stress that can be applied relative to the number of cycles of exposure based on material properties. A sample S-N curve is included in Figure 11 (p. 24). The curve begins to level around 10^7 cycles, the region beyond which is known as the endurance region of the curve. Operation in the endurance region is considered safe for an infinite amount of cycles of exposure. The torque value at which the S-N curve levels is called the endurance limit and is often subject to design-specific adjustment factors that can decrease the endurance limit based on characteristics of the equipment.

The S-N curve along with appropriate adjustment factors can be used to see whether the torque observed at the turbine generator shaft due to the cycling of the large load is of concern. Operating the generator in the endurance region is generally deemed safe, whereas exposing the turbine-generator shaft to torques outside the endurance region risks damage and should be

FIGURE 10

Study-Based SSTI Example: Cycling Load Profile and Resultant Interactions



A 900 MVA generation unit with a single turbine, generator, and exciter was modeled in detail to ascertain whether there is potential for interaction with a new AI data center. The generator is determined to have a natural frequency of 14 Hz based on data from the generator owner. The AI training process is represented with a power oscillation with an amplitude around 200 MW at 1 Hz and 50 MW at 14 Hz, which results in the torque between the turbine and generator amplifying due to resonance at the shaft's natural frequency of 14 Hz. This figure shows the load profile and the associated SSTI growing to 4 pu torque. This level of interactions could result in shaft fatigue, shaft damage, or tripping of the generator unit through associated protections.

Source: Energy Systems Integration Group.

avoided. It is critical for utilities to coordinate with turbine-generator shaft manufacturers and generator owners to obtain unit-specific S-N curves and associated correction factors. If this information is not available due to the age of the equipment or manufacturer confidentiality concerns, conservative estimation by the manufacturer may be required.

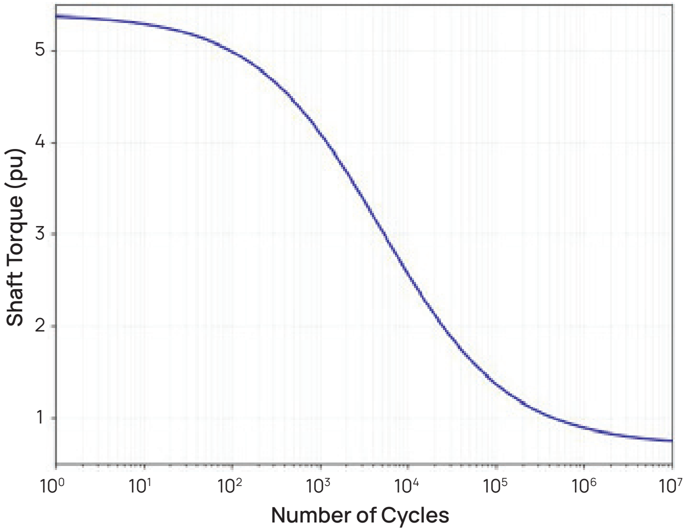
For SSCI, a frequency scan can be leveraged to determine whether any facilities nearby exhibit negative damping at frequencies near the large load cycling frequencies. If there is potential for negative damping, similar to the approach described for SSTI, a playback of various load profiles can be leveraged to identify frequencies of concern based on a wide-area EMT simulation.

Review of High-Frequency Cycling Limit Requirements

The project team's review of international standards demonstrated that understanding of high-frequency cycling is still growing, as standards were less established compared to VRT. In Canada, the Alberta Electric System Operator (AESO) draft requirements stipulate that large load facilities must be designed to avoid amplifying or contributing to oscillatory modes, including in the sub-synchronous and torsional frequency ranges of 3 Hz to 60 Hz. AESO's draft requirements further require that forced oscillation variability be limited to less than 16 kW/100 ms, with a total change limit of 160 kW permissible.

FIGURE 11

Sample S-N Curve



The S-N (stress vs. number of cycles) curve along with appropriate adjustment factors can be used to see whether the torque observed at the turbine generator shaft due to the cycling of the large load is of concern. Operating the generator in the endurance region is generally deemed safe, whereas exposing the turbine-generator shaft to torques outside the endurance region risks damage and should be avoided.

Source: Energy Systems Integration Group.

Fingrid's standard states that large load facilities must not cause amplification (negative damping) of power oscillations or cause cyclic power fluctuation. This includes in the 1 Hz to 15 Hz range for voltage fluctuations related to controller interactions with IBRs and resonance frequencies/torsional interactions in the 5 Hz to 45 Hz range.

The American Transmission Company (ATC) limits load active power oscillations for large load facilities over 200 MW to 25 MW over a period of less than 5 seconds.

Recommendation

The introduction of forced oscillations into the power system should not be permitted. This can be achieved by imposing requirements that significantly limit magnitudes and frequencies of forced oscillations. Large loads can be encouraged to leverage solutions such as compensatory devices (e.g., E-STATCOMs, battery energy storage systems, super capacitors, or rack-level storage) and control methodologies (e.g., software mitigation through the introduction of a secondary lower-priority computational process; hardware-level controls, GPU ramp-rate restrictions, or minimum power levels; or a combination of two approaches) to smooth out the load profile and reduce or prevent the introduction of forced oscillations and frequency control challenges.

If there is residual high-frequency cycling behavior that cannot be mitigated, or if the ISO/RTO and utility accept high-frequency cycling, requirements should be established to prevent the introduction of forced oscillations at frequencies and amplitudes of concern for subsynchronous phenomena.

A study-based approach can be leveraged to identify frequencies and amplitudes of concern that must be prevented in large load cycling profiles. These studies can be performed at the time of a large load interconnection assessment but heavily depend on accurate modeling, the availability of a large load profile, and an understanding of synchronous machine torsional oscillation withstand capabilities. In the absence of detailed models (such as turbine-generator shaft models), an appropriate approximated or generic model could be selected and a range of frequencies and amplitudes to avoid be determined. However, if approximations are leveraged, an additional margin may need to be added to the study findings. For example, if the study highlights an interaction at 14 Hz, a high-frequency avoidance range of 12 Hz to 16 Hz could be selected to account for discrepancies between physical and model parameters. The amplitude could also include a buffer. Similarly, if, for example, an S-N curve is available but the correction factors are not, then using conservative factors will be required.

Low-Frequency Cycling: Inter-Area Oscillations

Low-frequency forced oscillations can lead to the excitation of known inter-area modes on the power system, which can trigger resonance resulting in amplified oscillations across a given interconnection's footprint. These inter-area oscillations can in the most severe cases result in large negatively damped power swings that can cause cascading outages and large-scale system separation events. Examples of inter-area oscillation events and their impacts are included in NERC's *Interconnection Oscillation Analysis* report (NERC, 2019).

To safeguard the reliability of the power system, it is imperative that large load facilities not exhibit cyclic forced power oscillations that could potentially excite natural power system oscillatory modes and lead to resonance conditions.

The NERC Synchronized Measurement Working Group has highlighted major oscillatory modes across the Eastern, Western, and Texas Interconnections, which are included in Table 9.

Developing Low-Frequency Cycling Criteria

Cycling that can excite natural oscillatory modes must be prevented. Table 9 can be used as a guideline in the U.S. and Canada for which oscillatory frequencies to avoid in large load profiles depending on the location of the load facility.

Review of Low-Frequency Cycling Limit Requirements

In Europe, Fingrid and TenneT stipulate that in cases where a load facility could cause forced power oscillations or amplify existing oscillations in the low-frequency inter-area mode range, it shall be equipped with compensation devices (e.g., E-STATCOM, battery energy storage system, super capacitors, or rack-level storage) and/or adequate control functionalities. In the U.S., ATC notes that detailed studies may be required depending on the large load oscillatory profile and that mitigation measures could be implemented. In Canada, the AESO stipulates that large load facilities must be designed to avoid amplifying or contributing to oscillatory modes, including in the low-frequency range of 0.1-3 Hz.

TABLE 9

Major Oscillatory Modes Across Various North American Interconnections, as of November 2021

Interconnection	Mode Name	Mode Frequency Range (Hz)
Eastern	N-S	0.16–0.22
	NW-S	0.29–0.32
	NE-NW-S	0.23–0.24
Texas	N-SE	0.62–0.73
Western	North-South A (NSA)	0.20–0.30
	North-South B (NSB)	0.35–0.45
	East-West A (EWA)	0.35–0.45
	British Columbia (BC)	0.50–0.72
	Montana	0.70–0.90

Source: North American Electric Reliability Corporation, *Recommended Oscillation Analysis for Monitoring and Mitigation Reference Document,* Synchronized Measurement Working Group (2021), https://www.nerc.com/globalassets/who-we-are/standing-committees/rstc/smwg/oscillation_analysis_for_monitoring_and_mitigation_trd.pdf.

Recommendations

It is recommended that large loads not be permitted to introduce forced oscillations into the power system. This can be achieved by imposing requirements that significantly limit magnitudes and frequencies of forced oscillations. Large loads can be encouraged to leverage solutions similar to those described in the section "High-Frequency Cycling" to smooth out the load profile and reduce or prevent the introduction of forced oscillations and frequency-control challenges.

If there is residual low-frequency cycling behavior that cannot be mitigated, or if the ISO/RTO and utility accept low-frequency cycling, then requirements should be established to prevent the introduction of forced oscillations at frequencies and amplitudes of concern for major known interconnection inter-area modes.

Given that natural oscillatory modes are related to physical characteristics of the power system which continues to undergo significant changes, there is potential for change to existing known modes and the introduction of new modes. Therefore, ISOs/RTOs and utilities can also maintain the authority to update these modes of concern as the system evolves.

Reactive Power Requirements

Utilities and system operators establish reactive power requirements for generation and large load facilities to maintain voltage stability and ensure grid reliability, mandating that such facilities operate within certain reactive power limits. Given the size of large load facilities and their potential variability, there may be instances where dynamic reactive power support is required and deployment of different control modes is needed, respectively. These potential control modes include:

- Power factor control
- Voltage control
- Reactive power control

Developing Reactive Power Requirement Criteria

The need for voltage control is local—as opposed to the need for frequency control, which is addressed at a system level—and has been present historically going back to large industrial loads such as arc furnaces and aluminum smelters. Therefore, reactive power requirements for large load facilities are historically well established, including requirements dictating acceptable power factors and reactive power consumption limits at the POI. These established interconnection requirements drive appropriate facility and transmission connection requirements and ultimately form the basis for utilities' and system operators' operating philosophies. Given large loads' size, variability, and potential impacts, utilities and system operators need to include provisions for dynamic reactive compensation and various control modes in their large load connection requirements when studies highlight associated potential benefits or needs.

Review of Reactive Power Requirements

Table 10 (p. 28) summarizes the explicit reactive power requirements found in the standards reviewed by the project team, which also highlight specific provisions around facilities participating in demand response programs.

Recommendation

Utilities can continue their established approaches to reactive power capability–related connection requirements, which inherently inform their voltage control requirements and operating philosophies. They can use a study-based approach to determine when control modes need to be adjustable from power factor control to Q control mode and voltage control mode.

TABLE 10

Comparison of Reactive Power Requirements for Large Loads

Requirements	TenneT	RTE	Energinet	Fingrid	Ontario Independent Electricity System Operator	Alberta Electric System Operator
CONTROL MODES REQUIRED						
Mandatory control modes	- Voltage droop control mode - Reactive power control mode (constant Q)	- Power factor modulation mode - Voltage regulation mode - Reactive power modulation mode	Not specified	Not specified	Not specified	- Constant power factor - Voltage control - Reactive power set mode
STEADY STATE LIMITS						
Q consumption limit	Minimize Q	Must be ≤ 30% of max P[a]	Not specified	Minimize Q	Not specified	Based on power factor
Q generation limit	Minimize Q	Must be ≤ 15% of max P[b]	Not specified	Not specified	Not specified	Based on power factor
Power factor	Not specified	Not specified	Not specified	Must be capable of maintaining a power factor ≥ 0.99 or within agreed upon Q window[c]	Acceptable range: 0.9 lag to 0.9 lead	0.95 lag to 0.95 lead
Steady state Q exchange limits	Not specified	±5% of actual P	±15 MVAr	Not specified	Based on power factor	Based on power factor
CONTROL REQUIREMENTS						
Dynamic management of Q at POI	Not specified	Not specified	Not specified	Must manage Q at POI during P recovery to prevent over-voltage or under-voltage conditions	Not specified	Must manage Q at POI during P recovery to prevent over-voltage or under-voltage conditions
Rise time	0.1–10 s (adjustable)	Not specified	Not specified	Not specified	Not specified	Not specified
Settling time	1–60 s (max)	Not specified	Not specified	Not specified	Not specified	Not specified
Response time	Not specified	Not specified	Not specified	Not specified	Not specified	Not specified
Q gradient	Min 1 MVAr/min	Not specified	Not specified	Not specified	Not specified	Not specified

[a] For facilities participating in demand response programs, the load facility must have the capability to modulate Q up to -0.35 P_{max}.

[b] For facilities participating in demand response programs, the load facility must have the capability to modulate Q up to +0.4 P_{max}.

[c] These requirements do not apply during start-up and shut-down of the facility.

Source: Energy Systems Integration Group.

Voltage Phase Jump

System operators must maintain tight control of network voltage magnitude and phase relationships because sudden phase-angle shifts—caused by faults, switching events, line trips, etc.—can propagate through the system and destabilize equipment. To ensure that generators and large loads remain synchronized and do not trip or inject harmful transients during these events, operators impose phase-jump withstand requirements on generator and load facilities that specify how much abrupt phase-angle change the equipment must tolerate while continuing to operate stably.

Similarly to IBRs, large electronic loads use phase-locked loops (PLLs) in their interface with the grid to synchronize with the AC transmission system by tracking the fundamental frequency current and voltage waveforms. During sudden voltage phase shifts, the PLL aims to maintain or quickly re-establish synchronism.

If PLLs are unable to maintain synchronism with the AC transmission system, the large load facility will lose the ability to control active and reactive power proportions at the POI, which can adversely impact the power system. For example, if the PLL fails to appropriately track the fundamental voltage waveform, the active and reactive power consumption could be altered to the point that results in excessive reactive current injection or withdrawal that could lead to high-voltage or low-voltage conditions, respectively.

Determining Voltage Phase-Jump Withstand Criteria

A study-based approach could be leveraged to determine maximum expected changes in voltage angles for recognized contingency and operational events noted above. Weaker parts of the system can be analyzed for more limiting cases to inform the establishment of a single requirement to cover the entirety of the system. Otherwise, a study-based approach would be needed for each interconnection.

In addition, similar to the approach noted above for frequency ride-through, the large load voltage phase-jump withstand requirement could be established based on the requirement of ±25 degrees for IBRs, documented, for example, in IEEE 2800 and NERC PRC-029.[4]

Review of Voltage Phase-Jump Withstand Requirements

As noted above, IEEE 2800 and NERC PRC-029 both require IBRs to be designed to tolerate voltage phase angle jumps of ±25 degrees. These standards could also be adopted for large load facilities and would foster consistency in approach. In North America, the AESO explicitly adopts this criterion for large load facilities.

In Europe, there is a more varied set of requirements: ±20 degrees for Energinet, ±30 degrees for TenneT, and ±30 degrees for Fingrid. The other standards reviewed by the project team did not specify voltage phase-jump requirements at this time.

Recommendation

ISOs/RTOs and utilities can perform an initial analysis to identify the maximum voltage phase angle jump on their system for recognized planning and operational events. If the observed phase jumps exceed the ±25 degrees established by IEEE and NERC for IBRs, a jurisdictional-specific requirement can be implemented. Otherwise, the IEEE and NERC requirement for IBRs can serve as a standard for large loads as well.

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[4] https://www.nerc.com/globalassets/standards/approved-standards/prc/prc-029-1.pdf; https://standards.ieee.org/ieee/2800/10453/

Monitoring Requirements

Power system operators need high-resolution measurement and monitoring equipment at generator and large load facilities to accurately capture fast electrical phenomena that cannot be seen with conventional supervisory control and data acquisition (SCADA)—such as sub-cycle voltage and frequency excursions, converter control interactions, and rapid changes in active and reactive power. These high-granularity data streams give operators the visibility required to validate models, diagnose abnormal behavior, and ensure that both generation and large loads remain compliant with performance requirements during disturbances, thereby supporting reliable system operation as the grid becomes increasingly power electronics–dominated.

Monitoring requirements are usually established in terms of location of measurement/monitoring equipment, data points (e.g., time-stamped phase-to-ground voltages, phase currents), data resolution, duration of capture, and retention policies.

Large load facilities can exhibit behaviors that could impact reliability, including high variability in power consumption, load cycling, and sensitivity to system voltages. Therefore, high-fidelity monitoring information is vital to understand real-time behavior, facilitate meaningful investigatory analysis following system events, and serve as a feedback mechanism for accurate facility models. These quantities are above and beyond typical power quality measurement requirements.

Determining Monitoring Requirements Criteria

Many large load facilities have a high composition of electronic load; therefore, a similar approach to that taken for IBR monitoring could be appropriate for large loads.

Many large load facilities have a high composition of electronic load; therefore, a similar approach to that taken for IBR monitoring could be appropriate for large loads.

IEEE 2800 Table 19 and NERC PRC-028 include requirements for high-resolution data for IBRs for quantities that are continuously recorded and requirements for quantities that are recorded for a limited duration based on specific triggers. These data are required to be stored for a specific period of time, required to be retrievable, and not required to be streamed to the connecting utility. Similar criteria exist in NERC PRC-002 for bulk electric system generation facilities.

In addition to recorded measurements, given the potential for forced oscillations (covered in the section "Ramp Rates, Variability, and Cycling" above), obtaining streaming data from large loads can support real-time oscillation monitoring tools. Phasor measurement units (PMUs) and advanced digital fault recorders (DFRs) are capable of recording and streaming information with the necessary resolution.

Review of Monitoring Requirements

Examples of varying large load monitoring requirements from specifications reviewed by the project team are as follows (see Table 1 (p. 4) for the information sources).

- Fingrid requires the continuous recording of active power, reactive power, and voltage and frequency quantities at a large load facility's POI at a sampling frequency of at least 50 Hz. During transient events, sampling frequency of current and voltage measurements increases to a minimum of 4 kHz. Data must be readily accessible for analysis.
- EirGrid requires the installation of a disturbance recorder that measures high-voltage current and voltage quantities when outlined in the project-specific protection specification. The sampling rate is not specified.
- ERCOT issued a notice of "Requirement for Disturbance Monitoring Equipment Installation and Configuration for Large Loads" requiring the installation of PMUs, sequence of events recording equipment, and digital fault recorders for loads with a single-site peak demand of at least 75 MW. Detailed requirements are further elaborated in ERCOT's Nodal Operating Guide Section 6.
- ATC requires the large load to monitor the net of all loads at the large load facility at a resolution appropriate for recording 90 days of data, including phase and positive-sequence quantities for voltage and current, bus frequency, and active and reactive power measurements. The sampling rate is not specified.
- The AESO requires the installation of PMUs and streaming of specific synchrophasor measurements as specified in its connection rules, while also requiring continuous and trigger-based recordings of quantities to comply with PRC-002 and the associated ISO rules.

Recommendation

Large loads need to install monitoring devices that can stream and record high-fidelity data and maintain recorded data for at least 20 days, consistent with NERC PRC-028 requirements for IBRs. The sample rates must respect the Nyquist rate. Given the potential for high-frequency oscillations, a minimum sampling rate of 100 Hz should be applied.

Large Load Modeling Requirements

To accurately capture fast, nonlinear, and control-driven behaviors that materially affect system stability, transmission owners and system operators increasingly need high-fidelity positive-sequence phasor-domain (PSPD) models (e.g., PSS®, PSLF™) and full EMT models (e.g., PSCAD/EMTDC, EMTP) of generators, large loads, and critical transmission assets. As the grid integrates more power electronics–based resources and large, dynamic loads, these detailed models become essential for assessing grid stability, validating protection performance, assessing ride-through and recovery behavior, and ensuring that planning and operational studies reflect the true response of equipment under severe disturbances.

Fidelity, in dynamic modeling, refers to the degree to which a model accurately represents the physical behavior and response of a real-world plant or load. There are several considerations when selecting an appropriate model fidelity. First, it may not be necessary or feasible to capture the dynamic response of every individual load within a bulk power system, depending on the study's objectives. Simplifications in modeling can be beneficial, for example, representing wind power plants with a single generator equivalent model for bulk system studies, which provides an average response of all wind turbine generators within the plant. Additionally, computational constraints should be acknowledged: while PSPD models used in dynamic simulations may not fully capture the complexity of actual asset behavior, this limitation is generally acceptable for many system studies, particularly those focused on slower dynamics, such as the characteristics of dynamic recovery, rather than the detailed conditions during the transient events.

For large load dynamic models used in power system studies, it is crucial to achieve a high degree of fidelity to actual plant behavior for accurate analysis and reliable system planning. This ensures that the models can effectively capture the impacts of various study scenarios, thereby aiding in the development of robust strategies for system reliability and efficiency.

To ensure that large loads can be reliably interconnected to the grid, transmission planners need to perform dynamic assessments using reasonably accurate dynamic models of all grid-connected equipment including the large loads. A major challenge in modeling these new large loads is the lack of detailed information about their composition and the equipment used in these facilities, combined with the limited availability of dynamic models in existing PSPD and EMT simulation tools. For large load dynamic models used in power system studies, it is crucial to achieve a high degree of fidelity to actual plant behavior for accurate analysis and reliable system planning. This ensures that the models can effectively capture the impacts of various study scenarios, thereby aiding in the development of robust strategies for system reliability and efficiency. Without accurate models, it becomes difficult to analyze load behavior and the possible impacts on system reliability.

The focus in this report is on modeling requirements that are developed by transmission owners, operators, utilities, and not load modeling itself. The latter is covered in detail in the ESIG Large Loads Task Force report *Large Load Modeling for Dynamic Studies: Current Practices and Recommendations.*[5]

Developing Large Load Facility Model Requirements

Different levels of modeling detail are needed for different studies.

- **PSPD models:** Positive-sequence studies using lumped models are commonly used for steady-state operation analysis, load flow studies, bulk power system dynamic stability assessments, and voltage stability analysis. These studies focus on the overall system behavior and do not require the level of detail provided by EMT simulations.
- **EMT models**: EMT simulations with detailed component-based models are essential for analyzing switching operations, fault conditions, and lightning strikes. These studies require accurate representation of instantaneous voltage and current values and are crucial for understanding the behavior of components during fast transient events.

Furthermore, studies of specific phenomena, such as subsynchronous resonance (SSR) or SSCI, require EMT simulations with detailed models to accurately capture the interactions between components and the system in specific frequency ranges.

In addition, EMT models with detailed component-based representations more closely reflect the physical assets. Therefore, they can be used to validate positive-sequence models under a wider range of conditions and scenarios where real-world testing is not feasible. Table 11 highlights key features and considerations when deciding between PSPD and EMT models.

TABLE 11

Applications of PSPD and EMT Models to Large Loads

Feature	PSPD Models	EMT Models
Simulation type	Time-domain, phasor-based	Time-domain, solving differential equations
Time scale	Slower transient stability phenomena and steady-state operation	Very short time scales, fast transient phenomena
Modeling detail	Simplified, lumped parameters, average values	Detailed, instantaneous values, captures switching dynamics
Control system modeling	Typically models outer control loops	Capable of including fast inner-loop controls
Simplifications	Uses simplifying assumptions due to larger time step and positive-sequence nature	Avoids classical simplifications, captures more detailed dynamics due to smaller time step
Computational burden	Computationally efficient, suitable for large-scale studies	Computationally intensive, typically limited to smaller systems or specific parts of the network

Source: Energy Systems Integration Group.

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[5] https://www.esig.energy/large-loads-task-force/modeling/.

TABLE 12

Energinet Key Model Specifications for Large Loads

Model Type	Key Requirements for Large Loads
PSPD model	• 60-second simulation capability • All control/protection functions • Fault ride-through representation • Time step: 1–10 ms • Fully aggregated model acceptable • No user-defined models accepted
Harmonic model	• Frequency range: 50–2500 Hz • Resolution: 1 Hz • Impedance: positive, negative, zero sequence • Operating points: 0%, 50%, 100% power
EMT model	• PSCAD/EMTDC platform • Time step: 10 μs • Switching dynamics or average model • Semi-aggregated model acceptable (if justified) • Snapshot/multiple run compatible • User-defined model required • No global variables permitted

Source: Energy Systems Integration Group. Information summarized from Energinet, “Technical Regulation 3.4.3–Requirements for Transmission-Connected Demand Facilities, Revision 1. Doc. 24/06143-12,” Effective beginning November 1, 2024 (Fredericia, Denmark), https://en.energinet.dk/media/ep3ofgzp/17_07437-64-dcc-appendix-1d-simulation-model-approved.pdf.

Review of Large Load Modeling Requirements

Given that not all of the standards reviewed by the project team thoroughly covered the topic of model requirements, this section limits itself to referencing the requirements of the most comprehensive standards, those established by Energinet and the AESO.

Energinet’s standard specifies that large load facilities must provide the following models to facilitate system impact studies: a static model, PSPD model, harmonic model, and EMT model. These models must comply with the key specifications captured in Table 12. All models must be benchmarked across different simulation platforms (EMT vs. PSPD) and validated against actual measurements to ensure accuracy and reliability for study purposes.

The AESO provides very detailed model requirement criteria. Tables 13 and 14 (p. 37) include details on model components and requirements and model applicability by study type.

TABLE 13

AESO Model Components and Requirements for Large Loads

Aspect	PSPD Model	EMT Model
Primary model type	• Western Electricity Coordinating Council (WECC) Composite Load Model (CMLD) • Project-specific user-defined model (UDM)	• Detailed component-level representation • High-resolution time-series models
Load representation	• Constant power (P) load if all machines use variable-frequency drives (VFDs) • Model non-VFD machines ≥5 MW as machines	• High-resolution load profiles for each major load group • Time resolution to capture sub-second fluctuations • Worst-case loading scenarios • Separate profiles for information technology (IT) load, cooling load, motor load, etc.
Detailed component representation	• Power electronics and uninterruptible power supply (UPS) represented *functionally*, without necessarily capturing internal switching and fast controls	• UPS system controls (inner/outer loops) • Phase-locked loops • AC/DC and DC/DC converters with controls • Static switches and bypass circuitry • Variable-speed drive systems
Protection and control	• Load-shedding model • Basic protection representation	• Detailed protective functions/relays • Operational behavior representation • Control interactions
Plant equipment	• Simplified transformer representation • Aggregated reactive compensation	• Main power transformers with saturation characteristics • Grounding transformers • Harmonic filters • Tap-changer controls • Plant control with delays

Source: Energy Systems Integration Group. Information summarized from Alberta Electric System Operator, "AESO Connection Requirements for Transmission-Connected Data Centres," Draft for Stakeholder Review, August 22, 2025, https://aesoengage.aeso.ca/49634/widgets/209340/documents/157140.

TABLE 14

AESO Model Study Applicability for Large Loads

Study Type	PSPD Model	EMT Model
Power flow & steady-state	✔	✘
Short circuit	✔ Fault current calculations	✔ Detailed fault analysis
Voltage stability	✔ Post-transient margin analysis	✘
Transient stability	✔ Dynamic response (¼ cycle timestep)	✘
Switching studies	✔ Basic switching events	✔ Switching transients and coordination
Ride-through	✔ Voltage/frequency ride-through	✔ Detailed ride-through behavior
Power quality	✘	✔ Harmonics, flicker, ramping
System strength	✘	✔ Recovery time assessment
Subsynchronous resonance	✘	✔ Subsynchronous resonance (SSR)/torsional interactions
Forced oscillations	✘	✔
Control interactions	✘ Limited	✔ Detailed control dynamics

Source: Energy Systems Integration Group. Information summarized from Alberta Electric System Operator, "AESO Connection Requirements for Transmission-Connected Data Centres," Draft for Stakeholder Review, August 22, 2025, https://aesoengage.aeso.ca/49634/widgets/209340/documents/157140.

Recommendation

Standards need to be established that require large load facilities to provide appropriate steady-state and dynamic PSPD, harmonic, and EMT models, with accompanying high-resolution load profiles.

At this time, there is limited availability of mature generic library models,[6] insufficient data for model development and parameterization, a lack of standard submission requirements (outside of Energinet's and AESO's specifications), and missing model validation protocols. Industry can adopt the following steps to enhance current modeling practices:

- Develop standardized large load modeling requirements, including consideration of study type and type of fidelity required
- Develop generic library models suitable for bulk system reliability studies
- Develop and implement model quality assessment, benchmarking, and validation frameworks, similar to those used for IBRs
- Enhance industry collaboration
- Integrate modeling requirements into interconnection processes

The ESIG Large Loads Task Force report *Large Load Modeling for Dynamic Studies: Current Practices and Recommendations* further elaborates on large load modeling development, challenges and next steps.[7] (ESIG, 2026).

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[6] Generic library models available in standard power system simulation software packages are normally employed for transmission planning studies involving a large network and thousands of generators, loads, and other dynamic components. They are also deployed as approximations for behavior by facility type in EMT and PSPD studies (e.g., wind generator, battery, synchronous generation).

[7] https://www.esig.energy/large-loads-task-force/modeling/

Summary

By incorporating updated performance requirements in response to new behaviors on the power system, system operators and utilities can support the integration of large loads while safeguarding the reliability of the power system.

The dialogue between the power system industry and emerging large load industries such as AI and crypto mining organizations continues to lead to a mutual understanding of behaviors, capabilities, limitations, and needs. These exchanges have led to purposeful technological advancements in facility design which will support large loads meeting recommended performance requirements.

Table 15 (p. 39) shows a summary of the recommended interconnection performance requirements for large loads.

TABLE 15

Recommended Performance Requirements for Large Load Interconnection

Category	Recommendation	
Voltage ride-through	Regional transmission organizations (RTOs), independent system operators (ISOs), and utilities can develop voltage ride-through curves for high- and low-voltage conditions based on local, delayed, and remote fault-clearing times on a given part of the power system; respected contingency events; active power recovery timing; and automated post-contingency actions.	
Multi-disturbance ride-through	Large load owners can exclude or disable disturbance counter–based grid disconnection protections in designs. If they are interested in including disturbance-counter logic in their protection designs, they can set the counter threshold to cover multiple events or reclosure operations, with agreement of the transmission owner/operator.	
Active power recovery	RTOs, ISOs, and utilities can establish active power recovery criteria considering an appropriate system voltage and configurable recovery timing based on system strength. For example, large loads could be required to reach at least 90% of their pre-fault levels when post-fault voltage levels reach 0.9 pu within a default of 1 s or a specified timing based on system capability.	
Frequency ride-through	RTOs, ISOs, and utilities can adopt IEEE 2800 and NERC PRC-029 requirements for inverter-based resources related to frequency ride-through and rate of change of frequency (RoCoF) tolerance as minimum standards for large loads. This will ensure consistent performance and continued coordinated system responses to frequency excursions, which are interconnection-wide phenomena.	
Ramp rates and variability	**Minute-to-minute and non-cyclical second-to-second variability**	RTOs, ISOs, balancing area authorities, and utilities can examine broader load-following, frequency regulation, and voltage control capabilities when establishing ramp rate criteria. The collective effect of large load variability can be significantly higher than individual facilities, and a continuous system-wide evaluation is required to ensure that reliability is maintained.
	High-frequency cycling	RTOs, ISOs, and utilities can prohibit large loads from introducing forced oscillations into the power system and encourage large loads to leverage solutions to smooth oscillatory behavior at the facility level. If there is residual high-frequency cycling behavior that cannot be mitigated, or if the regional system operator and utility accept high-frequency cycling, they can establish requirements to prevent the introduction of forced oscillations at frequencies and amplitudes of concern for subsynchronous phenomena.
	Low-frequency cycling	RTOs, ISOs, and utilities can prohibit large loads from introducing forced oscillations into the power system and encourage large loads to leverage solutions to smooth oscillatory behavior at the facility level. If there is residual low-frequency cycling behavior that cannot be mitigated, or if the regional system operator and utility accept low-frequency cycling, they can establish requirements to prevent the introduction of forced oscillations at frequencies and amplitudes of concern for major known interconnection inter-area modes. Natural oscillatory modes are related to physical characteristics of the power system, which continues to undergo significant changes. Changes to existing known modes and introduction of new modes may occur. Regional system operators and utilities can maintain authority to update these modes of concern as their systems evolve.
Reactive power capability	Utilities can continue their established approaches to connection requirements related to reactive power capability, which inherently inform voltage control requirements and operating philosophies. A study-based approach can be used to determine when control modes need to be adjustable from power factor control to Q control mode and voltage control mode.	
Voltage phase-jump withstand	RTOs, ISO, and utilities can perform an initial analysis to identify the maximum phase jump on their system for recognized planning and operational events. If the observed phase jumps exceed the ± 25 degrees established by IEEE and NERC for inverter-based resources, a jurisdictional-specific requirement can be implemented. Otherwise, the IEEE and NERC requirement for inverter-based resources can serve as a standard for large loads.	

(CONTINUED)

TABLE 15 (CONTINUED)

Recommended Performance Requirements for Large Load Interconnection

Category	Recommendation
Monitoring	Large load owners can install monitoring devices that can stream and record high-fidelity data and will need to maintain recorded data for at least 20 days, consistent with NERC PRC-028 requirements for inverter-based resources. The sample rates must respect the Nyquist rate. Given the potential for high-frequency oscillations, a minimum sampling rate of 100 Hz should be applied.
Modeling	RTOs, ISOs, and utilities can require large load facilities to provide appropriate static, positive-sequence phasor-domain dynamic, harmonic, and electromagnetic transient models, along with accompanying high-resolution load profiles. There is limited availability of mature generic library models, insufficient data for model development and parameterization, a lack of standard submission requirements, and missing validation protocols. Industry can adopt the following steps to enhance current modeling practices: • Develop standardized modeling requirements • Develop generic library models suitable for bulk system reliability studies • Implement model validation frameworks • Enhance industry collaboration • Integrate modeling into interconnection processes

Source: Energy Systems Integration Group.

References

NERC (North American Electric Reliability Corporation). 2025. “Characteristics and Risks of Emerging Large Loads. NERC Large Loads Task Force White Paper.” July 2025. https://www.nerc.com/globalassets/who-we-are/standing-committees/rstc/whitepaper-characteristics-and-risks-of-emerging-large-loads.pdf.

NERC (North American Electric Reliability Corporation). 2019. *NERC Interconnection Oscillation Analysis.* https://www.ercot.com/files/docs/2019/10/02/Interconnection_Oscillation_Analysis_NERC.pdf.

For links to the established or draft system operator requirements reviewed for this report, see Table 1 (p. 4).

Large Load Performance Requirements: Current Practices and Recommendations

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

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This report is available at https://www.esig.energy/reports-briefs/large-load-interconnection-performance-requirements/.

To learn more about ESIG's work on this topic, please 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.

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