ESIG
Large Loads
Task Force

ESIG
ENERGY SYSTEMS
INTEGRATION GROUP

Large Load Performance Requirements

Current Practices and Recommendations

EXECUTIVE SUMMARY

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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 inter-connection requirements for large loads to avoid adverse impacts on grid reliability in the future, as well as costly

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Large Load Performance Requirements: Current Practices and Recommendations

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 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.

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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

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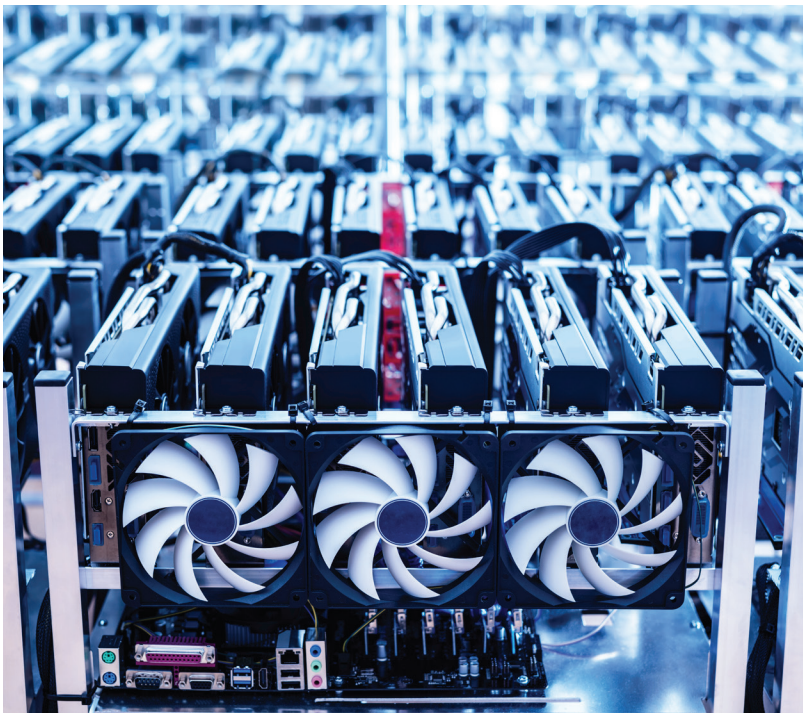

requirements; and developed recommendations for a minimum set of requirements for large load facilities.

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*.

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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

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.

- **Voltage phase jump**: the ability of a facility to withstand sudden changes in phase following switching operations or disturbances
- **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.
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 ES-1 (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.

Large Load Performance Requirements: Current Practices and Recommendations, by the Energy Systems Integration Group's Large Loads Task Force, is available at www.esig.energy/reports-briefs/large-load-interconnection-performance-requirements/.

To learn more about ESIG's work on large loads, please see https://www.esig.energy/working-groups/large-loads/ or send an email to info@esig.energy.

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