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Large Load Performance Requirements: Methodology and Framework

INTERIM REPORT

Contents

Key Audiences

Industry Stakeholders Involved in the Interconnection of Large Loads

- Resource and large load owners
- Resource and large load developers
- independent system operators, regional transmission organizations, and vertically integrated utilities
- The North American Electric Reliability Corporation (NERC) and the Federal Energy Regulatory Commission (FERC)
- Third-party consultants that work with the above stakeholders

Major Challenges Addressed by This Report and the Cost of Inaction

- Large flexible loads are interconnecting at high rates and include loads such as data centers, hydrogen production, the electrification of industrial heating needs, electric vehicle fleet charging, and manufacturing. Like any other large grid user (e.g. generators) or device (e.g. transmission assets) large loads may have an impact on the grid reliability. One critical aspect of a reliable grid is its ability to maintain frequency and voltage within normal ranges. When large generation resources or large loads are disconnected from or connected to the grid suddenly, it can cause local frequency and voltage to move outside of normal ranges and it must be quickly brought back within this range.
- To maintain a reliable grid, electricity system operators require generation resources to meet certain requirements when they interconnect to the grid. The requirements spell out how the generation resource must behave during normal and abnormal operations. However, the current regulatory landscape in North America contains significant gaps in the reliable interconnection of large wind, solar and battery storage resources, and yet larger gaps exist for large load interconnections.
- Continuing to interconnect large loads to the power system, without filling current gaps within interconnection and performance requirements will introduce significant uncertainty in the performance of these large loads and potentially lower the overall reliability of the power system.
- Currently there is no formal plan or methodology for incorporating best practices into interconnection performance requirements.
- Existing generator interconnection requirements for wind, solar, and battery energy storage can be used as a starting point for those for large loads. Similarly, international load connection requirements can be used as a starting point, and then be reviewed and adapted to better suit the North American power system.

Critical Needs for the Reliable Interconnection of Large Loads

- We largely lack large load–specific interconnection and performance requirements in North America.
- We also lack clarity around the behavioral characteristics of large loads, and thus the associated impacts on reliability. It is unclear which behavioral characteristics can be changed or shifted to reduce or eliminate the impacts on grid reliability and which are unchangeable, based on physical characteristics of the facility, and therefore it is critical for system operators responsible for creating requirements to fully understand current and future limitations of each large load technology.
- Technology-specific nuances related to large loads need to be better understood and considered to inform enhancements to the current technical minimum reliability needs for the both the large-scale transmission system and local distribution power systems.
- The arrival of high shares of large loads will require changes to numerous aspects of grid planning and operation including:
    - Load forecasting
    - Outage forecasting
    - Under-frequency load-shedding schemes, that is, system operator plans for removing load from the system to recover system frequency during extreme events
    - Changes in “typical” system dispatches
    - Cyber security
    - Interconnection performance requirements
    - Planning for expected operations (operability analysis), for example, flexibility requirements, frequency regulation requirements, any potential stability concerns
- Currently there is no formal plan or methodology for incorporating best practices into interconnection performance requirements.

The Cost of Inaction

- Delaying the development of interconnection requirements today may result in the costly application of requirements retroactively, as was the case with wind and solar generation in the past. Large transmission connected generation and load plants are typically designed and constructed to meet whichever requirements are applicable at the time of the plant’s interconnection. Therefore, the longer requirement enhancements are delayed, the number of potential non-compliant plants requiring potentially extremely costly upgrades will increase.
- Negative grid reliability impacts from existing large loads, if left unaddressed, may also impact acceptance of future large load developments, with system operators imposing more demanding requirements or even issuing moratoriums for large load connections in some regions. For example, in Ireland data center loads are not allowed to connect in Dublin for time being.

Key Stakeholders, and the Way Forward

Key Stakeholders

- Large load developers and owners are key stakeholders for this effort, as it requires an understanding of large load equipment, performance, capabilities, and limitations due to underlying processes and risks of equipment damage.
- System operators and vertically integrated utilities are another group of critical stakeholders for this effort, which requires understanding of system minimum reliability needs as those relate to large load connections.

Encouraging Enhancement to Current Large Load Interconnection Performance Requirements

- Through analysis of specific reliability needs of power systems and capabilities and limitations of large loads.
- Providing recommendations for requirement enhancements based on detailed analysis of current North American and international requirements.

Major Sections of the Report

Introduction

Large loads add complexity to an already rapidly changing power grid. While some countries and regions (including Ireland, the UK, France, and others) have been working on the integration of large loads for a number of years, system operators in North America are just beginning to address these new complexities and their implications for grid reliability. This project will draw from a review of existing generation interconnection requirements in North America as well as apply international large load interconnection requirements to the North American power system to help ensure transmission system reliability efficiently and effectively.

Changing North American Large Load Landscape

In this section we will summarize the trends in large load interconnections as seen in interconnection queue data throughout North America, including a high-level breakdown of large load types and relevant regional observations and trends. It will include:

- Data showing large loads currently in the interconnection queue by region
- Data showing actual interconnected large loads by region
- High-level breakdown of the type" of large load, whether electric vehicle fleet charging, data center, AI data center, manufacturing, green hydrogen, etc.

New Considerations Regarding Large Loads

This section will introduce new considerations from the power system's perspective that must be mitigated in order to reliably interconnect large loads in North America, including:

- Non-conventional load performance (for example, how large loads behave during large disturbance events on the grid (such as a short circuit fault or a large power plant tripping offline))
- Load variability
- Fleet-wide behaviors (such as scheduled power consumption, automatic removal from service based on power price triggers, power consumption changes due to data center usage, etc.)
- New cyber-security considerations

Key Findings and Recommendations

This section will summarize the key findings and recommendations as determined through the analysis outlined below.

Reliability Impacts of Increased Numbers of Large Loads

Estimating Trends in the Rapid Interconnection of Large Loads

This section will review current trends and future estimates for large load interconnections in North America. It will include a review, by region, of current interconnection queue data for large load interconnection as well as estimates for future large load interconnections. These trends will be analyzed by expert contributors to provide insight into potential gaps and mitigation measures and will include lessons learned from the international community.

The section will:

- Summarize trends in large load interconnection
  - Large load types (AI, data center, hydrogen, etc.)
  - Regional breakdown of large load interconnection queues
  - Estimates for actual interconnections based on historical data
- Provide analysis leveraging international experience and lessons learned to assess potential reliability risks as the number of large loads goes up

We will work closely with another project team of ESIG's Large Load Task Force (LLTF), focusing on data collection.

Linking NERC Disturbance Reports to Large Loads

Since 2016, NERC has published numerous "major event reports" that detail unexpected reductions in wind and solar generation in response to normally cleared transmission system disturbances—that is, situations in which wind and solar plants tripped offline following a grid disturbance, thus exacerbating a disturbance that would have been easily mitigated if the wind and solar had remained online (had ridden through the fault).[1] While these reports focus on inverter-based generation, large loads also interface with the transmission system via power electronics, and it is likely that large rectifier-based loads are also similarly susceptible to tripping (or switching to back-up generation) which creates a generation and load imbalance in the same way tripping of generation does. This section will review NERC's major event reports for solar and wind to assess which causes of reduced output may also be applicable to the sudden cessation of large loads. These potential causes of load reduction can then be analyzed along with estimates of levels of large loads in a given area to determine the size and scope of potential large load–related major reliability events.

The section will:

- Summarize the causes of output reductions observed in NERC reports for solar and wind resources, and quantify potential impacts of large loads tripping (or switching over to back up generation) for similar causes, which will help quantify potential reliability risks associated with large loads and their potential contributions to major system events

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[1] https://www.nerc.com/pa/rrm/ea/pages/major-event-reports.aspx

Summarizing System Operators' Experience with Large-Load Ride-Through Failures

This section will present information on already observed large-load ride-through failures on the North American power system (e.g., the Electric Reliability Council of Texas (ERCOT) and PJM). This will provide North America–specific real-world examples of potential reliability risks associated with non-conventional performance of large loads during grid disturbances.

To develop this section we will:

- Work with ERCOT to present information and analysis from a 1,600 MW major event involving large loads near Odessa, Texas, in December 2022[2]
    - Reduced load was a mix of large flexible loads
    - System frequency rose suddenly to 60.235 Hz, which is well outside normal operating ranges and shows the severity of the generation and load imbalance
    - There were difficulties obtaining data from load customers.
        - Due to a lack of data from the large load customers, ERCOT engaged industry and academic experts who provided an initial determination that the failure of these large loads to ride through was due to the equipment not being designed with sufficient ride-through capability
- Work with PJM to present information and analysis form a 1,500 MW major event involving large loads that occurred in July 2024.
    - 1,500 MW loss was spread across 25-30 loads ranging from 2 to 85 MVA each,
    - System frequency rose to 60.047 Hz and
    - Higher voltage levels required capacitors to be switched out, to avoid post-contingency voltage level violations.
- Work with other system operators to document other instances of load failing to ride through normally cleared transmission system faults

Assessing Potential Reliability Impacts of Large Loads with New Behaviors

Large loads such as data centers, electric vehicle fleet charging, etc. introduce new behaviors to the transmission system when compared to conventional loads. This section will describe these new behaviors and their potential effects on the transmission system, as well as what mitigations[3] may be necessary to ensure transmission system reliability under high levels of large transmission-connected loads.[4] These behaviors include but are not limited to:

- Oscillatory behavior of some large loads
- A lack of ride-through capability during large disturbance events on the grid
- Load variability, and unexpected large, sudden increases in demand which can create imbalance between load and generation that may drive system frequency out of normal ranges

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[2] ERCOT December Operations Report

[3] Mitigations can be but are not limited to: enhancements to large load interconnection requirements, enhancements to underfrequency load shedding schemes, updates to outage scheduling methodologies, etc.

[4] https://www.epri.com/research/products/000000003002028905

- Greater price-sensitivity than other resources, including sensitivity to external markets/jurisdictions, which can cause sudden load and generation imbalance that must have mitigation plans
- Increased marginal fuel sensitivity, as some large loads try to avoid consumption in jurisdictions with emitting resources on the margin, which can cause unplanned outages during time periods different than those in current planning assumptions

North American Grid Reliability Needs

Given the rapid increase of transmission-connected large loads, stakeholders in the North American power system must make enhancements to both interconnection requirements and planning procedures to ensure system reliability through the energy transition.

Uniform Technical Minimum Interconnection Requirements for Large Load Performance

- Performance
  - During normal and abnormal operating conditions
  - Voltage and reactive power support
  - Frequency support
  - Power oscillation damping
  - Active power ramp rate limitations
- Active power consumption behaviors
  - Oscillations due to changes in demand (primarily AI loads)
  - Rapid changes due to underlying process demand
  - Fleet behavior
- Ride through
  - Criteria to remain grid-connected through system disturbances
  - If the large load trips or switches over to back up fuel sources, a coordinated return to grid
- Power quality
- Blackstart/restoration scheme participation (if applicable)
- Return to service after a resource disconnection
- Performance monitoring and reporting

Improvements to Modeling of Large Loads

- A brief mention (since this will be addressed by a separate project team)
- To be linked to the large load modeling project team’s work within ESIG LLTF

Analysis of Existing Global Load Connection Requirements

The North American power system is lagging behind international power systems in both utility-scale solar and wind generation and large load interconnections, allowing stakeholders in North America to observe, analyze, and leverage international experiences to create high-quality enhancements to large load interconnection requirements. This section will review mature international large load interconnection requirements for similarities and considerations that could be incorporated into potential interconnection requirements in North America. In this section, proposed North American large load interconnection requirements will be reviewed and compared to international requirements to assess strengths that could be highlighted or potential gaps that should be mitigated.

Summary of Existing International Large Load Interconnection Requirements

This section will provide a brief overview of the international regions that have already established large load interconnection requirements.

Review of Large Load Interconnection Requirements in Germany

This section will review the large load interconnection requirements in Germany and assess whether and how these requirements could be applied to the North American System.

- German requirements for the connection of electrolysis facilities[5]
  - VDE-AR-N 4120/4130
- Inclusion of reactive power requirements and limits
  - Section 5.5
  - Section 10.2.2.2
    - Varied but standardized reactive power capabilities
  - Section 10.2.2.4
    - Ability to have Q dispatched by the grid operator
- Well-defined normal operating conditions
  - Section 10.2.1.1
- Specific requirements for consideration:
  - Hybrid facilities (large load plus generation, storage, etc.) are handled by placing requirements on the plant as a whole.
  - Voltage regulation settings and software status must be defined and "traceable."
  - The range between minimum and maximum short circuit power is specified by the grid operator.
  - ROCOF ride through requirements that do not restrict participation in load shedding.

[5] https://www.netztransparenz.de/en/About-us/Studies-and-position-papers/Requirements-for-the-connection-of-electrolyser-facilities

Review of the European Network of Transmission System Operators for Electricity (ENTSO-E) Demand Connection Code

This section will review the ENTSO-E large load interconnection requirements and assess whether and how these requirements could be applied to the North American System. Its review will include the following requirements in the ENTSO-E code:

- Commission Regulation (EU) 2016/1388[6]—Establishing a Network Code on Demand Connection
    - Annexes include criteria
- Clear processes are given for exemptions when needed for network stability.
- Frequency-related requirements should be uniform across all voltage levels.
- Maximum short-circuit ride-through capability is specified by the Transmission System Operator (TSO).
    - Maximum and minimum short circuit current estimates are provided by the TSO.
    - The TSO notifies load of unplanned events (compare this to NERC Milestone 2: PRC-030).
- "Appropriate and proportionate" compliance testing is required In accordance with Article 37(1)(b) of Directive 2009/72/EC
- Requirements and capabilities are at the load interface and should include:
    - Operational ranges
    - Automated responses
    - Data exchange requirements
- Harmonized grid connection rules are prioritized, both legally and technically.
    - Regional specificities also need to be considered when establishing network connection rules.
    - Voltage operation ranges should be set and coordinated between interconnected systems as they affect each other.
- The requirements promote coordination between transmission system and distribution system in operations.
- New regulations apply only to new facilities and are not retroactive.
    - A specific TSO may choose to apply requirements to existing large loads based on evolving system requirements and a full cost-benefit analysis.
- Detailed requirements are provided for the following categories:
    - General frequency (frequency operating range)
    - General voltage (voltage operating range)
    - Short circuit
        - Operating range estimates
        - Maximum short circuit current the load must ride through
    - Reactive power requirements
    - Protection requirements (protection takes precedence over controls)

[6] https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32016R1388

- Control requirements
- Information exchange
- Disconnection and reconnection
- Power quality
- Simulation models

ERCOT's Proposed Large Load Connection Requirements[7]

This section will review ERCOT's proposed large load connection requirements and compare them to the international requirements. This comparison will include discussions of any differences between the ERCOT requirements and international requirements and how applicable international requirements could be adapted to enhance reliability in ERCOT under high penetrations of large transmission-connected loads. Information and materials from ERCOT, primarily its Large Flexible Load Task Force (LFLTF), will be leveraged in this section,[8] including the following aspects of ERCOT's proposed requirements:

- Improvements to the speed and efficiency of load interconnection processes
  - Implement a new large load interconnection study process
- Improvements to load forecasting
  - Implement new demand forecasts including price responsive forecasts and require large loads (over 25 MW) to provide additional information to ERCOT
- Improvements to voltage ride through
  - Implement a new voltage ride-through standard for loads larger than 75 MW
  - Utilize IEEE 1668 criteria as a starting point[9]
  - ERCOT proposes that large, power electronic–based loads must use constant current control and may not use constant power control, s proposal adapted from NERC, the California Mobility Center, and the Western Electricity Coordinating Council's EV Charging Recommendations[10]
- Frequency control improvements
  - Create a path for large loads to participate in the ERCOT market as "controllable load resources"
- Ramp rate limits
  - Create new ramp rate standards for large loads that are not controllable load resources
- Considerations for large load behavior during emergency conditions
  - Ensure that large loads do not exacerbate abnormal system conditions
  - Proposed new "registered curtailable load" category that can be utilized prior to load shedding

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[7] https://www.ercot.com/committees/tac/lfltf

[8] https://www.ercot.com/files/docs/2022/10/21/LFLTF_Operations_Requirements_Oct2022.pptx and https://www.ercot.com/files/docs/2023/05/30/LFLTF_Large%20Load%20VRT.pptx

[9] https://standards.ieee.org/ieee/1668/6798/

[10] https://www.nerc.com/comm/RSTC/Documents/Grid_Friendly_EV_Charging_Recommendations.pdf

Adapting International Requirements to the North American Power System

The rapid increase in large load interconnection on the North American power system necessitates an effective and efficient enhancement to current large load interconnection requirements. While it may not be appropriate to directly adopt international requirements, these requirements can be adapted and modified to fit within the current North American regulatory paradigm.

Overview of and Lessons Learned from Existing North American Interconnection Requirements for Solar and Wind Generation

While large load interconnection requirements in North American are in their infancy, stakeholders have been working to enhance interconnection requirements for solar and wind plants in an effort to increase power system reliability. These interconnection requirement enhancements include detailed requirements for performance, capability, and ability to ride through (remain connected during) grid disturbances. Both the regulatory processes for completing these enhancements and the technical specificity should be thoroughly understood and leveraged to enhance the interconnection requirements for large loads.

Brief Overview of the North American Regulatory Landscape

This section will begin with a high-level review of the regulatory landscape in North America, including:

- How FERC, NERC, and regional requirements fit together
- Current efforts to enhance generator interconnection requirements

A Brief Review of NERC, FERC, and Regional Generator Interconnection Requirements

This section will review relevant NERC, FERC, and regional generator interconnection requirements to find commonalities and determine which requirements could be efficiently adapted to enhance the reliability of large loads on the system.

- Brief summary of North American regulatory structure
  - Major stakeholders (FERC and the Electric Reliability Organization (ERO) enterprise) and how they work together
- FERC orders, directives, agreements, and procedures[11]
  - Large generators[12]
    - *Pro forma* Large Generator Interconnection Procedures (LGIP)[13]
    - *Pro forma* Large Generator Interconnection Agreement (LGIA)[14]
  - Small generators[15]
    - *Pro forma* Small Generator Interconnection Procedures (SGIP)[16]
    - *Pro forma* Small Generator Interconnection Agreement (SGIA)[17]

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[11] https://www.ferc.gov/electric-transmission/generator-interconnection

[12] https://www.ferc.gov/electric-transmission/generator-interconnection/final-rules-establishing-and-revising-standard

[13] https://www.ferc.gov/media/pro-forma-lgip

[14] https://www.ferc.gov/media/pro-forma-lgia

[15] https://www.ferc.gov/electric-transmission/generator-interconnection/standard-interconnection-agreements-and-procedures

[16] https://www.ferc.gov/media/pro-forma-sgip

[17] https://www.ferc.gov/media/pro-forma-sgia

- FERC Order 2023[18]
- FERC Order 901[19]

- NERC standards and guidance
  - NERC FAC-001-4[20] and FAC-002-4[21]
  - Potential Bulk Power System Impact of Electric Vehicle Chargers[22]
  - NERC Inverter-based Resource Performance Subcommittee Commissioning White Paper
- ERO Enterprise
  - Summarize recent enhancements to regional requirements
    - IEEE 2800-2022 adoption and adaption

Lessons Learned from Generator Interconnection Requirements

This section will cover lessons learned through the journey of developing interconnection requirements from inverter-based resources such as solar, wind, and batteries. The section will touch on challenges such as:

- Lack of harmonization
- Issues around a lack of interconnection requirements or lack of specificity
- Timing of interconnection requirement updates and their potential retroactive application
- Ensuring sufficient technical minimum requirements in an open and stakeholder-driven process

[18] https://www.ferc.gov/media/order-no-2023
[19] https://www.ferc.gov/media/e-1-rm22-12-000
[20] https://www.nerc.com/pa/Stand/Reliability%20Standards/FAC-001-4.pdf
[21] https://www.nerc.com/pa/Stand/Reliability%20Standards/FAC-002-4.pdf
[22] https://www.nerc.com/comm/RSTC_Reliability_Guidelines/EVStudyReport.pdf

Capabilities and Limitations of Large Loads to Take into Account

When determining the solutions necessary to meet the needs of the North American power system, it is extremely important to consider both the capabilities and limitations of large transmission-connected loads. Creating solutions without considering potential limitations of large loads can have detrimental effects on their adoption and interconnection. Thoroughly understanding large loads, and specifically, load technology–specific capabilities and limitations will allow for solutions to maximize current load technologies as well as leverage near-term technology advancements. This section will:

- Detail major categories of large load types (electric vehicle fleet charging, AI data centers, other types of data centers, green hydrogen production, etc.), including
  - Their capabilities
  - Potential limitations to conform with each of the requirements as covered in the previous section, distinguishing between limitations dictated by the process and limitations dictated by physical equipment
  - Potential mitigations, distinguishing between process-related mitigation and mitigations that require hardware/control software changes
  - Potential future technology advancements
- Discuss how limitations in performance or capability should be considered when creating regulatory enhancements

Recommended Interconnection Requirements for Large Loads

Based on large load capabilities and technology limitations as well as best practices and lessons learned covered in previous sections, this section will provide high level recommendations for interconnection requirements for large loads, addressing some of the key performance issues important for power system reliability.

Critical Next Steps

The final section will summarize key findings and outline critical next steps to ensure that the observed gaps and potential mitigations are implemented on the North American transmission system.

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Interim Report

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