Reliable Addition of Large Datacentric Loads (RALDL): Interconnection Requests and Studies Practices

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Version History

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06/22/2026	1.0	Initial version
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Review and Update Requirements

- Review: every 5 years
- Update: as necessary

Contents

1. Purpose

The electric industry welcomes the reliable and secure integration of new large loads yet recognizes that certain activities of loads could significantly impact the grid. The rapid addition of transmission-connected large load customers providing data services (e.g., data centers, crypto mining, artificial intelligence) is creating new electrical grid challenges related to:

- Resource adequacy (demand outpacing resources)
- Planning uncertainty (risk and resource impact)
- Cost allocation (who pays for related build-out cost)
- Unique operating characteristics (potential for disturbances)

The North American Transmission Forum (NATF) has developed a project plan which includes development of practice documents to guide members through the lifecycle for reliable integration of these loads to the grid. This load addition lifecycle begins with interconnection requests. Given there is currently no comparable set of industry requirements for load interconnections like those for generators, thorough interconnection study processes must be developed.

This document does not create, replace, or change any requirements in the NERC Reliability Standards or other applicable criteria, nor does it create binding norms by which compliance with NERC Reliability Standards is monitored or enforced. Implementation of NATF practices does not ensure compliance with the NERC Reliability Standards. In addition, this document is not intended to take precedence over any company or regional procedure. It is recognized that individual companies may use alternative and/or more specific approaches that they deem more appropriate.

2. Scope

This practice applies to all functions that are involved in evaluating or supporting interconnection requests for large datacentric loads prior to development of interconnection agreements. That may include, but is not limited to, the following functions: transmission planners, system protection, operations planning, transmission support, and tariff administration.

This document focuses on the first step, Interconnection Requests and Studies, of the Reliable Addition of Large Datacentric Loads (RALDL) project plan (see Figure 1). The document describes the process for interconnection applications, data requirements, dispositioning requests, administering the interconnection process, change management for requests, modeling techniques, appropriate studies including screening criteria, and interactions with internal and external personnel during the process.

The NERC Large Load Task Force (LLTF) developed the following definition for large loads in 2025 [1]:

"Any commercial or industrial 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 (BPS) 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."

For the NATF RALDL project, practice documents focus on transmission- or distribution-connected individual or aggregated datacentric loads totaling 50MW or more at a single site.

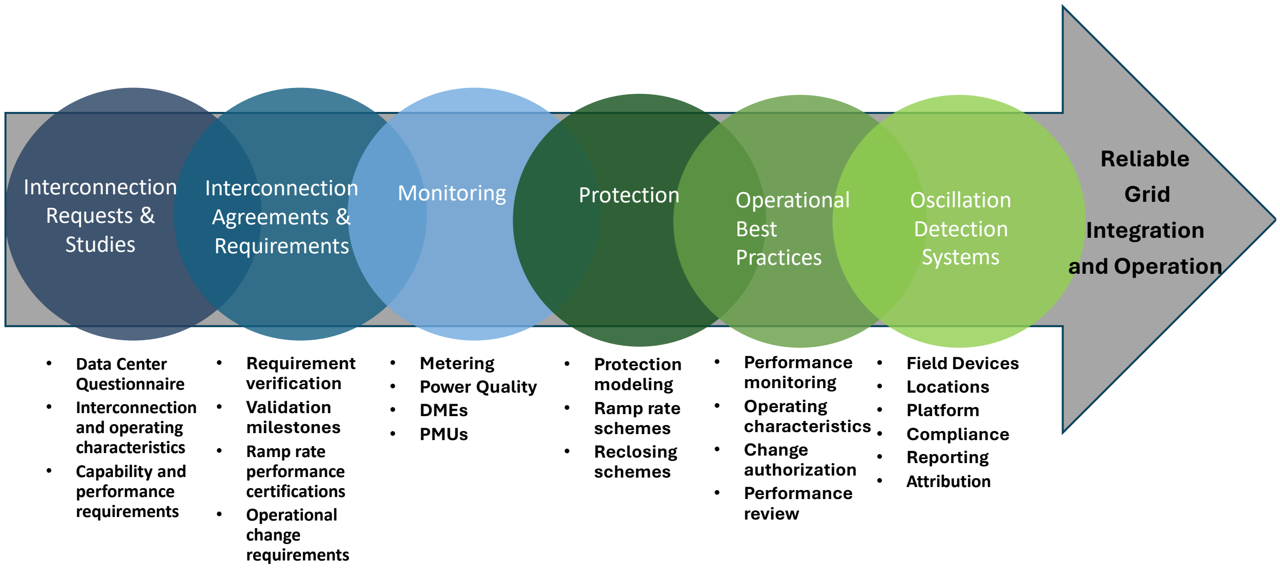


Figure 1. Reliable Addition of Large Datacentric Loads (RALDL) project plan

The proliferation of large datacentric loads is advancing rapidly, which poses challenges to established utility practices. The authors of this document acknowledge this pace and offer the practices defined herein as reference methods for the electric industry at the point and time of issue. With that acknowledgement comes the commitment to updating the document as practices for the interconnection of large datacentric loads continue to evolve.

3. Definitions

NATF Practice

A documented method for performing a process, under the same or similar circumstances, in a safe, effective manner where the requisite skills, diligence, prudence, and foresight are those that are reasonably expected from skilled and experienced industry organizations.

NATF Superior Practice

A leading industry practice that can be consistently applied under a range of circumstances and that is a safe, effective, and efficient process or activity for achieving near-optimal industry results in terms of quality, reliability, and maintainability.

Anticipated Aggregate Facility Demand

The total planned site or point of interconnection load over the project schedule for the interconnection to reach commercial operation.

Cryptocurrency Mining

The process of using IT equipment (e.g., computers, application-specific integrated circuits) to solve mathematical problems to validate and enable various transactions [2].

Data Center

A physical room, building, or facility that houses IT infrastructure for building, running, and delivering applications and services [2].

Data Certification

The practice of interconnection customers signifying the completeness and accuracy of interconnection request data.

Data Verification

The practice of the TO, TP, or PC reviewing interconnection request data submittals for completeness.

Facilities Study

An engineering study conducted by the TO, based on and including interconnection facilities and network upgrades identified in the cluster study, that details modifications to the TO's Transmission System required to provide the requested transmission service, including the cost and scheduled completion date for such modifications.

Facility

In this document, facility is used to denote sites with large datacentric loads.

Forced Oscillation

The forced response of a system to a periodic input [3].

Large Load Entity

Any entity that owns, designs, or operates large load facilities [2].

Large Load Operator

An entity that operates a large load facility [2].

Large Load Owner

An entity that owns or maintains a large load facility [2].

Large Load Tenant

An entity other than an owner that may lease or operate all or portions of a large load facility.

Model Validation

The process of comparing simulation results with measurements to assess how closely a model's behavior matches the measured behavior [2].

Model Verification

The process of confirming that model structure and parameter values represent the equipment or facility design and settings by reviewing equipment or facility design and settings documentation [2].

Most Severe Demand Contingency

The amount of load removed from the transmission grid following the worst single contingency in the data center facility.

Operational Flexibility

The ability of a load to control demand based on schedule, signals, or instruction as coordinated with the TO.

Per Unit (p.u.)

Quantity expressed as a fraction of a defined base unit quantity.

Phasor Measurement Unit (PMU)

A time-synchronized measurement device that estimates the magnitude and phase of an electrical phasor quantity like voltage or current [2].

Planning Coordinator (PC)

The responsible entity that coordinates and integrates transmission Facilities and service plans, resource plans, and Protection Systems [4].

Point of Interconnection (POI)

A point where the interconnection system connects a large datacentric load to the transmission system (derived from [5]).

Power Usage Effectiveness (PUE)

Illustrates the total energy used by a data center divided by the energy used by information technology used at that same data center [6].

Preliminary Screening Assessment

Initial evaluations completed prior to formal interconnection requests to assess the voltage and thermal performance of the currently planned system after interconnection of the new load for normal and contingency steady-state conditions and a specific in-service date and location.

Price Responsive

Behavior of a load facility where demand is dependent, in part or in whole, on energy prices [2].

Ramp Rate

The rate that a generator or load changes its output or demand. The units used to describe ramp rates are typically MW per second or MW per minute [2].

Site Control

The legal authority or permission to occupy, develop, or use a specific parcel of land or property [2].

System Impact Study

A collection of technical studies performed to assess the potential effect of interconnecting loads to the system.

Sub Synchronous Oscillations

System frequency variations that occur below the system's fundamental frequency.

Transmission Operator (TO)

The entity responsible for the reliability of its “local” transmission system, and that operates or directs the operation of the transmission Facilities [4].

Transmission Planner (TP)

The entity that develops a long-term (generally one year and beyond) plan for the reliability (adequacy) of the interconnection bulk electric transmission systems within its portion of the Planning Authority area [4].

Voltage Stability

The ability to maintain system voltage so that both power and voltage are controllable [7].

4. Interconnection Data

Detailed data for large datacentric loads is essential for evaluation of the interconnection to commence. Interconnection requests must include a wide range of general information about the interconnection customer, site, and technical data about the nature of the load and potential on-site generation, batteries, uninterruptible power supply (UPS) systems, on-site resources, and load models for adequate interconnection evaluations to occur. Accurate and complete data submittals lead to better interconnection studies and (potentially) a faster interconnection process.

General Information

Those responsible for interconnection evaluations (nominally TPs and/or PCs) should require general and project-related data planned for the facility at the time of interconnection request. See Appendix 1 for example templates related to general information.

Contact and Site Information

NATF Practices

4.1 Require pertinent interconnection customer contact information to facilitate communication:

- requestor contact information
- large load owner information
- tenant information

4.2 Require a technical lead be named to address questions that arise on data or models submitted as part of the interconnection request.

4.3 Require pertinent site information for study purposes and evaluation of request maturity:

- site location
- evidence of site control

Project Information

NATF Practices

4.4 Require pertinent project information for study purposes and scheduling:

- data center type (e.g. crypto-mining, hyperscaler, artificial intelligence)
- desired energization date

4.5 Use a standardized questionnaire for large datacentric load interconnection requests.

Technical Information

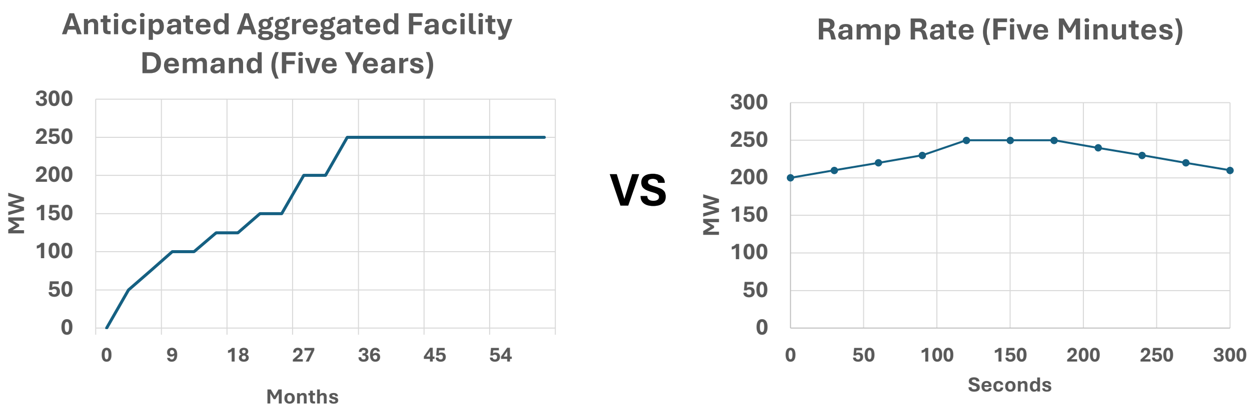
Those responsible for interconnection evaluations should also require more specific technical data as the interconnection process progresses. See Appendix 2 for example templates related to technical information.

Anticipated Aggregate Facility Demand

NATF Practices

4.6 Require the interconnection customer to communicate the planned project schedule for load over time by providing maximum anticipated aggregate facility demand on a seasonal basis in MVA with power factor for the first five years. This should also include overall peak anticipated demand over the first 10 years of interconnection and a forecast for seasonal demand for year 15 [8].

> Multiple terms involving demand over time are important to evaluate interconnection requests. Figure 2 illustrates the difference between demand variation through the buildout phase of a project over months or years (anticipated aggregated facility demand) with operational changes in demand in real time within seconds or minutes (ramp rate).



- **Project-related**
- **Measured in months or years**
- **Eventually constant without expansion**

- **Operations-related**
- **Measured in seconds or minutes**
- **Variable**

Figure 2. Anticipated aggregate facility demand vs ramp rate for an example 250 MW load

Detailed Load Behavior and Operational Flexibility

NATF Practices

4.7 Require the interconnection customer to communicate as much information as possible about the data center operational load behavior to those responsible for interconnection evaluations. including how the demand of the data center facility changes over time for normal and abnormal operation. The flexibility of large loads may also have significant implications on interconnection studies and processes ranging from equivalent treatment as firm load on one hand, to a fully dispatchable load that can rapidly follow dispatch commands on the other. Load profile and flexibility should be described in detail by providing the following information:

4.7.1 Provide max ramp over one second duration (MW/s) in both directions during normal operation.

4.7.2 Provide max ramp over one minute duration (MW/min) in both directions during normal operation.

4.7.3 Define the most severe demand contingency (i.e., how much load is removed from the transmission grid following the worst single contingency in the data center facility?).

4.7.4 Describe how electricity prices influence facility demand.

4.7.5 Disclose if the proposed data center will be operated in coordination with other data centers within the interconnection authority's footprint and provide load behavior details of all impacted data centers.

4.7.6 Describe how data center on-site backup generation (if applicable) is intended to be operated in relation to the transmission grid (e.g., full backup or partial backup when disconnected).

4.7.7 Describe how the facility can modify its demand to meet an externally provided objective:

- Curtail demand in a controlled manner
- Increase demand in a controlled manner (e.g., after curtailment or for system restoration)

4.7.8 Describe how the facility demand can be scheduled or forecasted in advance and over what time horizon (i.e., hours, days, or months).

4.7.9 Describe what mechanism(s) is/are employed by the load to control its demand.

- Disconnection of load, either in blocks or on an entire plant basis
- Direct control of loads, e.g. dynamic power targets for compute loads
- On-site energy storage to offset or increase net load demand
- On-site generation that can be dispatched to offset net load demand

4.7.10 Describe what constraints exist that affect the degree to which a load's demand can be modified in terms of minimum consumption level in MW (i.e., describe what portion of demand is fixed).

4.7.11 Describe the expected response time between receipt of the request/command to modify the load's demand and the load's demand meeting that request/command:

- MW response capabilities within five minutes, 30 minutes, 60 minutes, etc.
- Specify differences in response for local vs. central dispatch controls
- Specify the facility capability to receive and follow electronic dispatch commands (e.g., set consumption to X MW, consume no more than Y MW, consume at least Z MW)
- If the load is one of several loads managed by the same entity, specify whether demand curtailed at one load within the interconnecting authority's footprint would affect the consumption of the other loads managed by the entity (i.e., will demand be shifted from one load to another load?).

Load Components by Type

Large data center facilities represent complex, highly concentrated electrical loads with stringent requirements for reliability, power quality, redundancy, and scalability. Unlike conventional commercial or industrial facilities, data centers combine large continuous electronic loads with significant supporting mechanical and power-conditioning infrastructure. Major categories of loads typically present in a hyperscale or large enterprise data center include information technology (servers, storage, network hardware, etc.), lighting, power conditioning and distribution, cooling, and other auxiliary loads which support the balance of plant.

NATF Practices

4.8 Require the interconnection customer to communicate the percentage breakdown of total load consumption by component and load characteristics to ensure accurate modeling.

4.8.1 Provide the percentage breakdown of total MW consumption by the following components:

- computing / server load
- lighting load
- power distribution losses
- cooling load
- other auxiliary loads

4.8.2 Provide the percentage of the total facility load (MW) that is IT equipment during each season of build-out.

4.8.3 Specify if the data center has a forced cooling system and, if so, identify the type:

- Computer Room Air Conditioners (CRACs) with internal compressors
- Computer Room Air Handlers (CRAHs) supplied with chilled water
- Air-Handling Units (AHUs) dedicated to data center space
- direct liquid cooling (to chip or rack level)
- other (specify)

4.8.4 Identify how the motor components of the cooling system are driven:

- single-speed AC directly connected
- variable frequency drive (VFD) / inverter controlled
- other (specify)

4.8.5 Identify the power usage effectiveness (PUE) target at full build-out.

4.8.6 List the characteristics and MW (or %) of motor loads:

- large motors (>100 HP)—type, quantity, and starting method
- small motors (<100 HP)—type, quantity, and drive type

4.8.7 Specify key transformer characteristics for 1 MVA and above:

- nameplate rating (MVA)
- voltage ratio (primary / secondary)
- Impedance (%Z)
- tap changer type (OLTC, NLTC, or fixed)
- configuration (delta–wye, wye–delta–wye, or other)

4.8.8 Provide transformer test reports with saturation characteristics for all customer-owned transformers, as soon as available.

4.8.9 Provide the expected transformer inrush current magnitude and duration during initial energization and cold start scenarios.

4.8.10 Identify the planned redundancy configuration (e.g., N+1, 2N, 2N+1) for the electrical distribution system.

4.8.11 Identify the required service reliability (e.g., Tier I, II, III, or IV per Uptime Institute).

4.8.12 Identify the availability requirements (% uptime).

4.8.13 Provide the level of requested redundancy in terms of dual or multiple utility feeds and describe the preferred configuration (simultaneous, standby, etc.).

4.8.14 Provide composite load model key components [9]:

- Feeder Equivalent – Models voltage regulation from distribution substation to “majority” of the load
- Motor A – 3 phase compressors
- Motor B – 3 phase fans
- Motor C – 3 phase pumps
- Motor D – Algebraic representation of residential HVAC
- Electronic – Consumer electronics
- Static – Lighting, resistive heating etc.

Preliminary One-Line Diagram

An electrical one-line for a large-load facility should clearly show how power enters the site; how it is transformed, protected, distributed, and backed up; and how redundancy is achieved. The purpose is to give planners and engineers an accurate, non-intrusive, non-proprietary view of device configurations, load paths, protection boundaries, and the facility’s behavior during faults, switching events, and contingencies. A concise but complete one-line supports system reliability, proper fault-current coordination, voltage stability, and predictable behavior during load transfers or emergency operations.

NATF Practices

4.9 Require the interconnection customer to provide the following data in a one-line diagram:

- Point of interconnection (POI), bus configuration, and ownership demarcation to clearly show where utility power enters and how faults will be isolated.
- Main transformers with ratings (MW and MVAR), impedance, tap settings, and grounding method, since these define fault levels, voltage regulation, and system behavior under load.
- On-site generation, parallelling/switching mode, and interlocks, which govern load-transfer behavior and fault contributions.
- Advanced technologies such as static synchronous compensators or other FACTS devices, when applicable.

- Battery energy storage systems with an indication of whether advanced inverter functions (e.g., grid-forming) are enabled.
- Redundant distribution paths and tie-breaker logic, showing how the data center maintains service during N-1 events and how load transfers occur.
- Uninterruptible power supplies, transfer switches (automatic and static), harmonic-producing equipment, and any filtering, since these affect transient behavior and power quality.
- Protection zones, breaker locations, metering, and current and potential transformer placement to illustrate how faults are detected and cleared without impacting adjacent systems.
- Differentiation of central plant loads (cooling), lighting, and process/computational loads (e.g. GPUs).
- Transformation and voltage levels across tiers of distribution.

Reactive Devices

Data centers can have large inductive and power electronic loads, which can significantly influence the stability of the grid, and some facilities may employ active power factor correction onsite.

NATF Practices

4.10 Require the interconnection customer to provide the following information on reactive devices to enable interconnection evaluations and coordinate system operations:

- device nameplate specifications for all reactive power devices at the facility
- purpose of reactive power devices and control objective
- whether reactive components are fixed or variable
- anticipated real-time and historical reactive power demand based on comparable facilities
- anticipated instantaneous power factor and whether any power factor correction equipment will be utilized
- specifications for reactive power devices that will be configured as harmonic filters, including filter type, tuning frequencies, and control methodology
- power factor correction methods to address dynamic operational changes from datacentric loads

Short Circuit Ratings

Data centers have sensitive electronics and may include onsite generation. Understanding how the facility may impact the grid and any grid strength requirements is important for completing interconnection assessments.

NATF Practices

4.11 Require the interconnection customer to provide the following information to identify the short circuit impacts on the POI and allow study of the ability of the system to serve the load reliably:

- connecting transformer configuration

- data for each backup generator (energy storage) on the customer side of the POI including, size, impedance, type (inverter based, synchronous, etc.)
- whether backup generators will ever run in parallel with the connected utility system
- information on required minimum grid strength in terms of short circuit ratio (SCR) needed for data center operations

During the interconnection study, the utility will identify the maximum fault current availability of the planned interconnection as well as minimum N-1 fault current availability. The interconnection customer is expected to ensure its equipment is rated to withstand the maximum fault current, including margin for system growth.

Power Quality

Large datacentric loads will be subject to analysis demonstrating that they will not adversely impact the power quality of the electrical system. In general, objectionable power quality impacts are not expected when analysis indicates the power quality requirements listed in section 7 will be satisfied.

NATF Practices

4.12 Require the customer to provide the following basic technical planning data to evaluate the load with respect to harmonic distortion, voltage fluctuations and associated light flicker, rapid voltage change, voltage unbalance, and voltage and frequency variation ride through performance.

- Expected facility harmonic current injection spectrum, up to the 50th harmonic order, aggregated at the reference point of applicability.
- Expected magnitude and frequency of variations in active and reactive power, aggregated at the reference point of applicability.

Voltage Performance

Voltage performance under various system conditions must be specified and understood to evaluate interconnection requests effectively.

NATF Practices

4.13 Require the following voltage performance information including reconnection times to align with performance requirements such as ride-through [8]:

- Voltage sag level/duration at which the predominant load (computer/server loads) disconnects from the utility system.
- Voltage sag level/duration at which the cooling load disconnects from the utility system,
- Measurement method (per phase or three-phase RMS) for voltage sag levels used for disconnection.
- Voltage swell level/duration at which the predominant load (computer/server loads) disconnects from the utility system.
- Voltage swell level/duration at which the cooling load disconnects from the utility system.

- Measurement method (per phase or three-phase RMS) for voltage swell levels used for disconnection.
- Threshold number of voltage disturbances used to determine disconnection from the utility system.

Frequency Performance

NATF Practices

Similarly, frequency performance under various system conditions must be specified and understood to evaluate interconnection requests effectively.

4.14 Require the following frequency performance information including reconnection times to align with performance requirements such as ride-through [8]:

- Frequency level/duration below which the predominant load (computer/server loads) disconnects from the utility system
- Frequency level/duration below which the cooling load disconnects from the utility system
- Frequency level/duration above which the predominant load (computer/server loads) disconnects from the utility system
- Frequency level/duration above which the cooling load disconnects from the utility system

Site Generation and Storage Data

Large data centers supporting cloud computing, AI training, and financial transactions depend on reliable uninterrupted power supplies. A single voltage dip or loss of supply can cause massive server dropouts, data corruption, and cascading restart failures. As a result, large data centers typically integrate on-site generation and energy storage to ensure:

- continuity of service
- protection against grid disturbances
- compliance with utility ride-through and fault-current expectations
- support for black-start, islanded operation, and staged restart

From a grid-planning perspective, these backup systems materially affect:

- net load during contingencies
- fault contribution
- frequency and voltage response
- large load reliability (LLR) and fault-induced voltage recovery (FIDVR) risk

Uninterruptible Power Supply (UPS)

Since short-duration power disturbances can result in service outages, data corruption, or permanent equipment damage, UPS systems are also a fundamental component of data center electrical infrastructure. UPS systems protect data center loads from power interruptions, voltage sags/swells, frequency deviations, and waveform distortions, thereby ensuring continuity of operations and maintaining equipment reliability.

Modern data centers use layered backup architecture rather than a single technology. Typically, the hierarchy is: Utility grid → UPS / flywheel → on-site generation → energy storage → microgrid.

NATF Practices

4.15 Require the following information on datacenter UPS and backup generation:

- type(s) of UPS
- UPS computational load
- UPS capacity (MVA) and % of the facility load supported by UPS
- UPS input power factor (based on measurement, facility design or UPS parameter data)
- normal operation mode of the data center IT load
- IT/computing load battery design back up time (in sec)
- sag or swell manual or automatic reconnection to grid (explain the characteristics)
- time duration for load transfer to occur
- UPS trip conditions (i.e., trip values and duration)
- UPS architecture (i.e., centralized, modular, or distributed)
- UPS redundancy configurations (N+1, 2N, 2(N+1))
    - N+1: one additional UPS to back up a single failure
    - 2N: two completely independent UPS systems
    - 2(N+1): fully redundant plus backup for each system
- size of the data center emergency generator (EG) in relation to the data center load
- dispatchability of EG to support the entire/partial load during system events and for how long (hour)
- Are periodic operational tests conducted that involve actual load transfer through the UPS system?

Battery Storage

Utility-scale battery energy storage systems are mature technologies that provide longer-duration services such as peak shaving, frequency regulation, and grid balancing to help maintain system reliability over broad geographic areas. These solutions operate from cycles to hours and support the stability of the electrical grid by smoothing large-scale variability and enabling greater renewable integration. Inside facilities, battery storage operates in much the same way to mitigate the highly variable power profiles associated with datacentric workloads including emerging artificial-intelligence learning modes in data centers. Rather than contributing to regional energy balancing, facility-level batteries act within the plant to buffer fast transients, protect onsite generation, and maintain internal power quality. Battery storage should also be evaluated alongside other fast-response technologies—such as STATCOMs—that provide voltage stabilization and reactive support, helping determine the most appropriate solution for a facility's specific challenges.

UPS systems differ from battery storage in both purpose and design. A traditional UPS provides instantaneous ride-through capability and conditions voltage and frequency to shield sensitive electronics from even the briefest disturbances, relying historically on valve-regulated lead-acid batteries suited for very short discharge durations. Battery storage, in contrast, typically uses lithium-ion chemistries that support longer operation, faster recharge, and greater cycling flexibility. While UPS equipment bridges the gap to backup generation and prevents immediate outages, battery storage offers extended support, load shaping, and active power management that become increasingly valuable as facilities face growing grid constraints, higher power densities, and more erratic load behavior. Most datacentric facilities continue to depend primarily on UPS systems, with battery storage adoption still limited but expanding as needs diverge based on facility design and resilience objectives.

As compute demands become more volatile and grid conditions tighten, UPS architectures are evolving to incorporate attributes traditionally associated with battery storage, including lithium-ion energy modules and more adaptive power-electronics controls. This convergence has given rise to hybrid approaches that pair the instantaneous response of UPS systems with the longer-duration capabilities of battery storage. Grid-forming functionality is also beginning to play a role inside facilities: once confined to utility-scale systems, grid-forming inverters are increasingly deployed to respond within milliseconds to voltage or frequency deviations caused by fast load changes, helping stabilize both onsite generation and grid-connected operation.

NATF Practices

4.16 Require the following data related to onsite battery storage:

- Continuous/peak AC power (MW/MVA), duration (minutes/hours), and minimum/maximum state-of-charge constraints aligned to operational scenarios.
- Response-time and ramp-rate requirements, including voltage droop settings.
- Ride-through curves and settings.
- Coordination and confirmation of protection setpoints between the facility and the utility including over/under voltage/frequency trip points.
- Short-circuit and fault behavior: Expected fault current contribution (magnitude, duration).
- Power quality limits and filtering needs: Harmonics, flicker, and any reactive power/voltage support setpoints.
- Require PMU data including phasor angle/magnitude, voltage/current, frequency, timestamp resolution, sampling rate, event capture for PQ data related to voltage sags, voltage transients, harmonics, and flicker.
- Battery technology and life model: Chemistry (e.g., Li-ion variant), cycle/depth-of-discharge profile, round-trip efficiency, calendar/cycle life expectations, and degradation assumptions used for sizing.
- Safety, code, and compliance requirements including fire detection and suppression, gas detection/venting, and emergency protocol.

- Controls objective and philosophy which includes integration with internal building management requirements and interface with external SCADA and EMS systems, including system latency requirements.
- Dispatch authority who sends state of charge, available capacity, and operating limits to support forecast-aligned, dispatchable operation.
- Sequencing with UPS and generators, which includes islanding requirements, when this will occur (such as number of faults) and how system restoration occurs.
- Cybersecurity attributes for all data and control pathways (authentication, encryption, role-based access, secure interfaces, and audit logging).

Modeling Package Submittal

The modeling package submitted at the time of interconnection request is intended to represent the planned facility based on best available information or past submittals for comparable facilities.

NATF Practices

4.17 Require the following models for each interconnection request application:

- A validated power flow model
- A validated short-circuit model
- A validated RMS positive sequence dynamic model
- A representative EMT model that aligns with the positive sequence dynamic model

NATF Superior Practices

4.18 This superior practice redacted in open distribution version of the document.

Data Certification and Verification

Accurate and complete data from interconnection requests is essential for accurate interconnection studies and evaluations. Allowing interconnection requests with incomplete or inaccurate data leads to inefficiency and sets a poor example.

NATF Practices

4.19 Require interconnection customers to sign data submittals to attest that the submitted data is accurate and complete; signature represents acknowledgement that the submitted data will serve as the basis for interconnection studies.

4.20 Verify interconnection data with the interconnection customers prior to starting studies for interconnection. This includes, but is not limited to, reviewing data submittals for completeness as provided in requirements and flagging missing data for a response to the interconnection customer.

4.21 Commence any timeline commitments for completion of studies after the interconnection request data has been verified.

5. Interconnection Process

The overall interconnection process includes a variety of components including the application mechanism, the approach for evaluating multiple active requests (serial vs cluster), what constitutes a qualified change, and how to define the maturity of an interconnection request.

In the absence of comparable regulatory frameworks like the LGIA for generator interconnections, current practices vary widely for managing large load interconnection requests. The increase in the number, size, and demand for large data centers has driven unprecedented levels of interconnection requests. Without standardized approaches, speculative requests for interconnection may consume time and resources that could be better spent evaluating serious requests (see Figure 3).

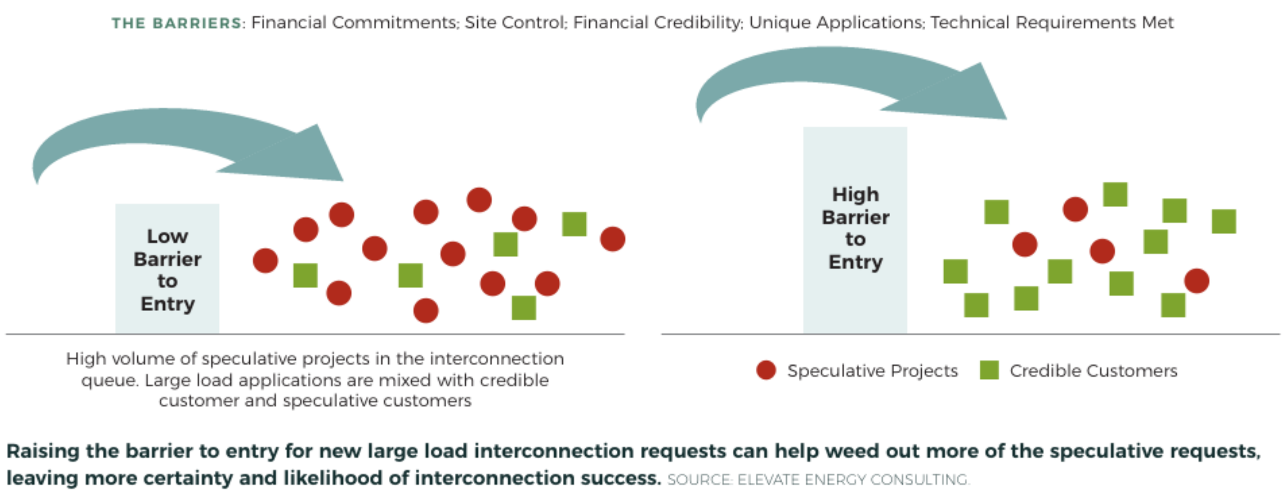


Figure 3. Illustration of speculative interconnection projects with a low barrier to entry [10]

Phases of the Interconnection Process for Large Datacentric Loads

The overall interconnection process for large datacentric loads can be summarized in seven phases as shown below:

- Interconnection request
- System impact study (including interim deliverability)
- Facility study
- Interconnection agreement*
- Construction*
- Commissioning*
- Commercial operation*

  * May occur in stages

Figure 4. Phases of the interconnection process for large datacentric loads

To start the interconnection process, applications must be submitted with adequate technical, project, and financial requirements included to proceed to subsequent phases.

Application Process

The application process involves several steps that assist the applicant in decision making and ensure appropriate data is collected for interconnection studies.

- Customer submits application form
- Customer submits detailed questionnaire(s) with required project and technical data
- Customer submits appropriate financial security

NATF Practices

5.1 Require interconnection applicants to become familiar with state-specific interconnection procedures for state jurisdictional projects.

5.2 Implement an electronically accessible interconnection application process.

> This acts as a formal process for the interconnection customer to submit an interconnection application.

5.3 Require a fee for the interconnection application.

> The application fee should cover administrative costs to process the application, which includes the cost of all steps preceding the signed study agreement.

5.4 Implement system impact study deposits using the following recommendations:

- Interconnections with a lower capacity (e.g., less than 100 MW) have a base deposit fee and a per MW adder
- Interconnections with a medium capacity (e.g., 100 MW – 500 MW) have a set deposit amount
- Interconnections with a higher capacity (e.g., greater than 500 MW) have a different set deposit amount

> Deposits are established by the individual TO and should increase with the increase in the load to be interconnected. Deposits should reflect the cost to administer and perform the studies associated with the application in accordance with comparable LGIA requirements [11]. The MW thresholds may be adjusted based on the size of the proposed interconnection compared to peak system load.

5.5 Implement project deposits that progressively increase as projects advance beyond system impact studies through the interconnection process to ensure the TO is kept whole in the event of a withdrawal. This may vary depending on jurisdiction, but guidelines for consideration would be 5 to 10% of network upgrade costs.

Evaluation Processes

The size and number of datacentric loads seeking interconnection varies significantly across North America (see Figure 5). In some regions such as Northern Virginia, Georgia, Texas, and Arizona, there may be dozens of interconnection requests per month, while other areas of the country only receive preliminary inquiries. To address this variability, establishing methods for screening applicants and appropriately handling the volume of applicants is important. This section introduces the concept of preliminary assessments for screening requests and compares elements of both the serial and cluster approaches to evaluating multiple active interconnection requests.

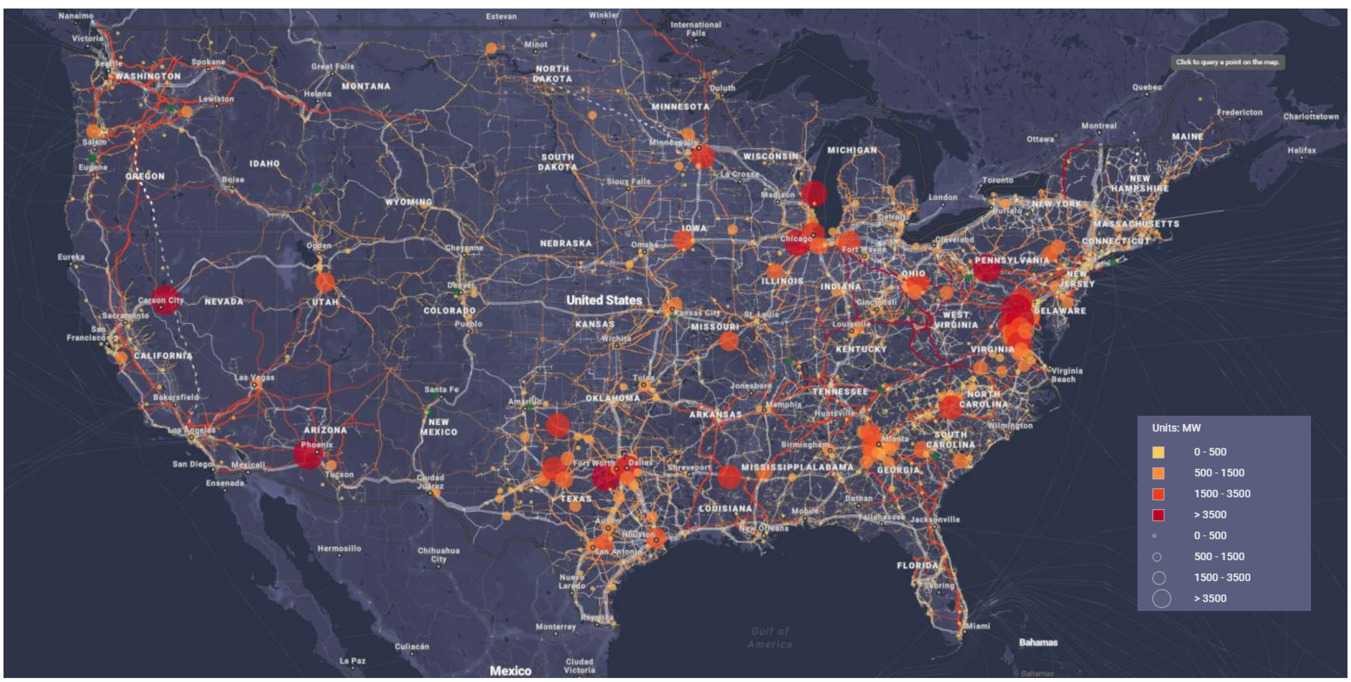


Figure 5. “Accelerating Speed to Power” - planned data center demand (December 2025) [12]

Preliminary Screening Assessments

Depending on the number, frequency, and magnitude of interconnection requests, TOs may elect to establish preliminary screening assessments as an initial step before formal studies. The purpose of the preliminary screening assessment is to evaluate the voltage and thermal performance of the currently planned transmission system using an approved case from the TO or RTO. Preliminary assessments may also include power quality and system protection screening studies based on the characteristics of the proposed interconnection location.

This evaluation could be done for normal and contingency (N-1 and N-1-1) steady-state conditions for a specific load amount, in-service date, and location as identified by the customer.

NATF Practices

5.6 Members should consider requiring a separate fee and request form for each separate location and/or year studied, as their tariffs allow.

5.7 Results of the preliminary screening assessment should include studies of voltage and thermal performance with the addition of the requested load for the year and location, along with identified facility upgrades necessary to correct reliability deficiencies considering the load addition.

5.8 Results of the preliminary screening assessment may also include power quality and system protection evaluation results as appropriate.

Resource Adequacy Studies

Resource adequacy is one of the fundamental challenges posed by the influx of numerous large datacentric loads. A variety of options may be considered to meet energy and capacity needs including short-term market purchases, demand response programs, additional generation resources (new or upgraded), and longer-term power purchase agreements. While transmission organizations have limited ability to address these challenges on the long-term planning horizon directly, they do have a responsibility to communicate potential impacts to those departments or organizations that have resource planning responsibilities. In addition, transmission organizations have responsibility for developing plans and mitigations to address resource adequacy for short-term planning and real-time operations.

Load Forecasting and Long-Term Resource Planning

NATF Practices

5.9 Become familiar with regional requirements and differing state-specific policies for resource planning.

5.10 Establish formal communications channels with entities responsible for generation planning to provide monthly updates on large load interconnection requests.

5.11 Leverage maturity process attributes to determine which load interconnection requests are communicated to generation planning.

5.12 Evaluate transmission constraints for available generation.

Tools for Addressing Resource Adequacy Concerns

NATF Practices

5.13 Ensure interconnection requests include information on how loads may address resource adequacy needs:

- interruption or curtailment capabilities of the facility
- onsite generation use (backup vs. peak shaving, etc.)
- rate structure(s) available to provide incentives for resource flexibility

Additional resource adequacy considerations, including short-term planning, onsite generation scheduling, and energy adequacy are beyond the scope of this interconnection practice document.

Processing of Requests

There are two approaches TOs can utilize to process interconnection requests: a serial approach and a cluster approach. In a serial approach, submitted interconnection requests are studied independently of or with limited consideration of other requests. Depending upon the volume of interconnection requests submitted, an interconnection request queue may be established. Benefits of a serial approach include flexibility in processing interconnection requests and simplified assignment of interconnection costs. The drawback of the serial approach is that it may not work well with multiple applicants.

In contrast, when utilizing a cluster approach, interconnection requests submitted within a defined window are grouped together and studied simultaneously in a single study. Benefits of a cluster approach include reducing study frequency, reducing queue backlogs, improved cost allocation of required system upgrades, setting minimum technical requirements early, and financial commitments, all of which establish commitment by those most serious about progressing to the next stage of interconnection. The drawback of the cluster approach is that it is more rigid and may take longer to set up the studies. TOs considering which approach is appropriate for their organization should consider the volume of requests submitted, organizational capacity to study and interconnect multiple customers at once, public policy, and organizational goals and objectives. As these factors change, TOs should evaluate the effectiveness of each approach for their organization.

Common Practices for Both Serial and Cluster Approaches

NATF Practices

5.14 Stakeholder engagement

5.14.1 Define how and when stakeholders will be engaged. Include a process for handling stakeholder questions and feedback.

5.14.2 Ensure all individuals within your organization are communicating the same message to stakeholders.

5.15 Commercial readiness

Commercial readiness requirements ensure that projects studied are viable and committed.

5.15.1 Require direct deposits or letters of credit at key milestones and clearly define refundability conditions and withdrawal penalties.

5.15.2 Require proof of site control, such as ownership, lease, or other means and require periodic updates if conditions change.

5.15.3 Request evidence of progress on permits, zoning applications, and major equipment purchases.

5.16 Technical readiness

Technical readiness ensures accurate modeling and efficient study execution.

5.16.1 Require complete and validated technical data, including single line diagrams and equipment specifications.

5.16.2 Define deadlines for data submissions.

5.16.3 Establish consequences for incomplete or inaccurate data, such as removal from the cluster or delay penalties.

5.16.4 Encourage early engagement on resolution of technical issues to reduce re-study risk.

NATF Superior Practices

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Practices for a Serial Approach

NATF Practices

5.18 Queue management

When there are enough interconnection requests to necessitate the establishment of an interconnection queue, it is important that interconnection requests are studied in the most efficient manner to reduce the amount of time applications are in the queue.

5.18.1 Establish internal targets for the completion of interconnection studies and monitor your ability to achieve these targets.

5.18.2 Define decision points in the interconnection process during which the large load entity will be required to make a decision regarding the future of their request. Establish a clear deadline for these decisions and the repercussions of not adhering to them.

5.18.3 Limit the number of speculative requests in the interconnection queue by either requiring requests to meet established commercial and technical readiness requirements or by establishing a process to perform preliminary screening assessments for developers.

NATF Superior Practices

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5.20 This superior practice redacted in open distribution version of the document.

Practice for a Cluster Approach

NATF Practices

5.21 Timeline

To ensure transparency and predictability in the cluster study process, establish clear timelines and communicate them to all stakeholders.

5.21.1 Define and publish the start and completion dates for each cluster study cycle. Conduct at least one cluster study annually, or more frequently if queue volume warrants.

5.21.2 Specify the duration for key activities within the study such as the length of the customer request window to join the cluster and the length of the customer engagement window for intake, scoping and coordination. Durations are usually expressed in days.

5.21.3 Clearly state that the cluster study does not replace requirements for other studies (e.g., facility studies, affected system studies).

5.21.4 Publish a milestone schedule at least monthly and provide regular status updates to stakeholders on progress if dates shift.

5.22 Cost allocation

Ensure fairness and transparency in cost-sharing among participants.

5.22.1 Cluster study costs should be clearly communicated prior to proceeding with the study, with a minimum payment required at the time of the interconnection request.

5.22.2 Allocate remaining costs based on the size of the request (MW capacity).

5.22.3 Implement escalating penalties for late-stage withdrawals to maintain queue integrity and discourage speculative participation.

NATF Superior Practices

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5.24 This superior practice redacted in open distribution version of the document.

Qualified Changes

This section discusses the process for determining and dispositioning qualified changes to large datacentric load interconnection requests.

NATF Practices

5.25 Define a process to identify when qualified changes to the large datacentric load interconnection require further evaluation or re-study, using the following factors as a guide.

- change in load MW
- change in data center function
- significant change in the percentage of composite load model components
- significant changes to ride-through characteristics or protection settings
- significant changes to UPS capabilities and transfer timing or characteristics
- significant changes to backup generation capabilities and transfer timing or characteristics
- significant changes to onsite storage capabilities or characteristics
- significant changes to onsite reactive power elements
- significant changes to transformer or tie line impedances
- hardware changes that require real-time digital simulator (RTDS) testing
- change in end-user facility topology [13]
- protection system changes impacting contingency definitions

Maturity Assessment Process

Given the potentially large number of interconnection requests with highly varied levels of certainty of completion, a process is needed to validate conformity with interconnection requirements before proceeding to subsequent stages.

NERC initially proposed the concept of a maturity assessment process to "…aid in deciding when large load projects should be selected for inclusion into various studies" in a draft version of their Large Loads Working Group Reliability Guideline [2]. This included definitions for the various phases of a large load interconnection lifecycle and clear criteria for determining the maturity of a project at each stage.

Throughout the lifecycle of a large datacentric load interconnection, key technical, financial, and project milestones must be met to transition successfully through stages of the process. Given the key phases for the interconnection of large datacentric loads as defined above, different maturity levels or stages provide indicators of the suitability for inclusion of a particular interconnection request in the next phase of the process and provide clear criteria for which future loads are considered in key studies and assessments.

NATF Practices

5.26 Require the maturity of the attributes listed in Table 1 before advancing to the applicable stages of the interconnection process:

Table 1. Maturity assessment attributes for various early stages of the interconnection process

Attribute	Category	Interconnection Request	System Impact Study	Facility Study	Interconnection Agreement
Data sharing agreements	Agreements				X

Attribute	Category	Interconnection Request	System Impact Study	Facility Study	Interconnection Agreement
Proof of agreement with datacenter	Agreements	X	X	X	X
Regulatory approval	Agreements				X
Financial security posted	Financial	X	X	X	X
Percentage of network upgrades funded	Financial			X	X
Detailed and realistic construction schedule	Project				X
Development permit status (local)	Project				X
Environmental permit (county/state)	Project				X
Design engineering 30% complete	Project			X	X
Design engineering 60% complete	Project				X
Proof of site control	Project	X	X	X	X
Detailed load schedule	Project	X	X	X	X
Completed screening study	Technical	X	X	X	X
Static and transient load models	Technical		X	X	X

5.27 Define interconnection maturity for latter stages of interconnection requests using attributes that include the following:

- interconnection agreements
- known customer
- construction status
- land status
- procured equipment status
- dynamic operational load profile
- resource adequacy confirmed

6. Interconnection Modeling

Interconnection modeling is crucial to enable adequate study of large datacentric load interconnection requests.

Positive Sequence Models Available for Large Datacentric Loads

Accurately representing data center loads in power system simulation software is key for adequate evaluation of impacts. This section discusses available models.

ZIP Load

The ZIP model is a static representation used in power systems to describe electrical loads as a combination of constant impedance (Z), constant current (I), and constant power (P) components. While it provides a convenient mathematical framework for analyzing load behavior, the ZIP model struggles to capture the dynamic, nonlinear, and time-varying nature of diverse loads like motors or consumer electronics, which means it masks the influence of motors on voltage dip and voltage recovery.

Composite Load

Composite load model (CMLD) is a dynamic load model that represents the aggregated behavior of different types of end-use loads (motors, electronic devices, static loads, etc.) connected through a distribution system. CMLD model captures the aggregate dynamic response of loads. It is more realistic than traditional static ZIP models because it captures how loads respond dynamically to voltage and frequency disturbances. It consists of the following key components:

- Feeder Equivalent – Models voltage regulation from distribution substation to “majority” of the load
- Motor A – 3 phase compressors
- Motor B – 3 phase fans
- Motor C – 3 phase pumps
- Motor D – Algebraic representation of residential HVAC
- Electronic – Consumer electronics
- Static – Lighting, resistive heating etc.

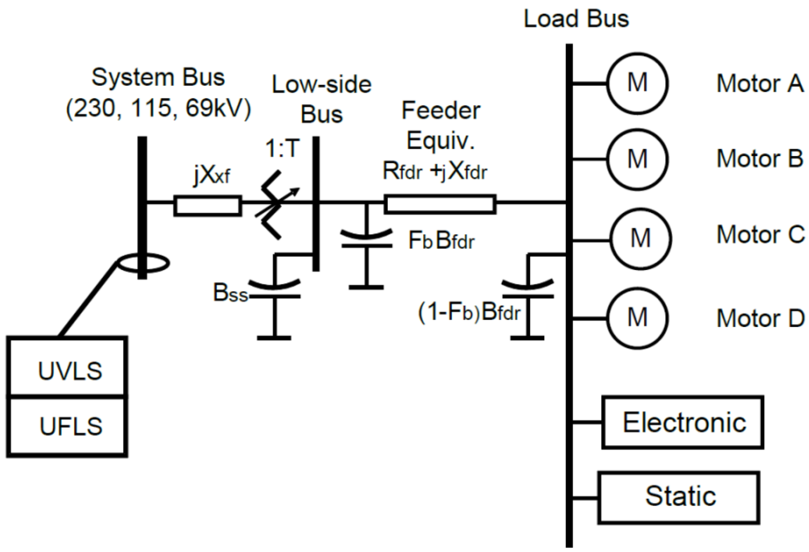


Figure 6. Composite load model (CMLD) overview [9]

Repurposed EV Model by ISO-NE

This data center model is based on an electric vehicle (EV) model [14]. The EV model captures the characteristics of power-electronic-based chargers, including their constant-power draw, voltage sensitivity, and potential disconnection or curtailment during disturbances. The model can be parameterized to reflect different charging technologies and aggregated charging stations, allowing planners to study impacts such as rapid demand ramps and harmonic distortion, as well as reconnection logic for high and low voltage conditions with associated ramp rates to reflect gradual recovery. By incorporating the EV model into dynamic simulations, system operators can evaluate how widespread EV adoption influences frequency stability, voltage recovery, and reserve requirements, ensuring that charging infrastructure is accurately represented in reliability and planning studies. The EV charger model allows independent adjustment of active and reactive power outputs.

The data center model includes several advanced features to better capture realistic system behavior. It can represent a second-order response, allowing for more accurate dynamic performance. The model supports both high and low voltage and frequency ride-through capabilities, ensuring the model can simulate how data center loads respond to a wide range of grid disturbances. The real and reactive power control loops are identical except for the presence of the droop block in real power control.

PERC1 Model

The acronym PERC1 denotes the Power Electronic Reconnecting and Ceasing load model [15], which is derived from the foundational model originally developed by the Electric Power Research Institute (EPRI). The EPRI model [16] captures the characteristics of power-electronic-based chargers, including their power draw, voltage sensitivity, and potential disconnection or curtailment during disturbances. The model can be parameterized to reflect different charging technologies and aggregated charging stations, allowing planners to study impacts such as rapid demand ramps, as well as reconnection logic for high and low voltage conditions with associated ramp rates to reflect gradual recovery. By incorporating the EV model into dynamic simulations, system operators can evaluate how widespread EV adoption influences frequency stability, voltage recovery, and reserve requirements, ensuring that charging infrastructure is accurately represented in reliability and planning studies. The EV charger model allows independent adjustment of active and reactive power outputs.

The PERC1 construct generalizes EPRI's earlier work related to electric vehicle charger loads in order to represent aggregated populations of diverse power electronic devices. Such aggregated load representations may include electric vehicle charging infrastructures (as originally intended) plus large-scale computational facilities (e.g., large datacentric loads or cryptocurrency mining operations) and extensive deployments of variable frequency drives [15]. The model is intended to capture the collective dynamic response characteristics of these electronically interfaced loads under system disturbances, thereby providing a scalable representation for bulk power system studies.

The model simulates load behavior in response to voltage changes. In addition, the MW control path incorporates a basic frequency droop with deadband to reflect possible load characteristics.

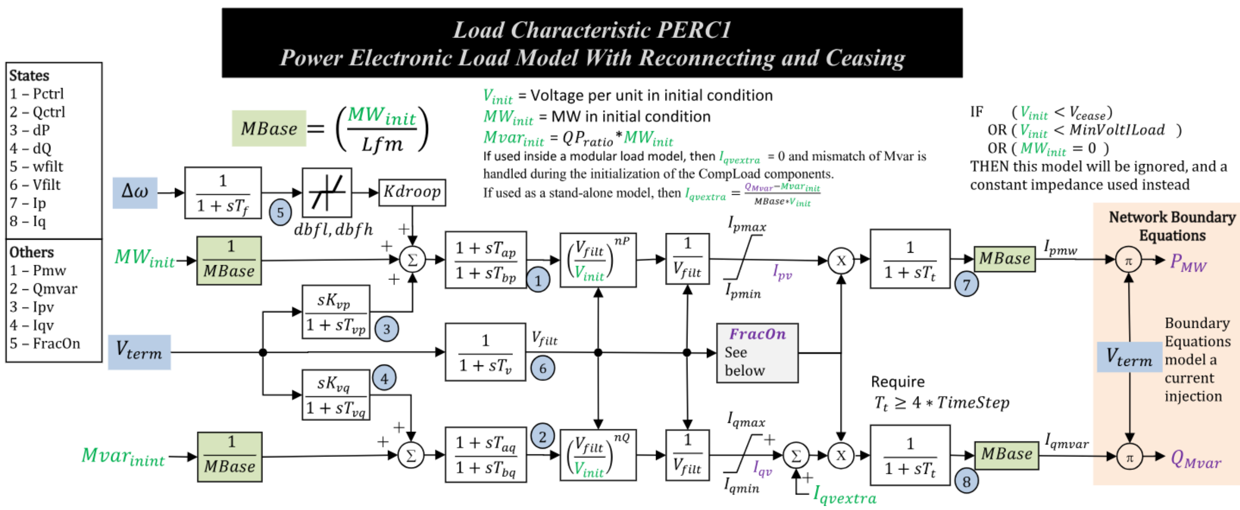


Figure 7. PERC1 model [15]

The FracOn model represents the cease-and-reconnect logic for load behavior under voltage disturbances (see Figure 8). When the filtered voltage stays below Vcease for longer than Tcease, part of the load is disconnected to the FracOn value of (1 - Fcease) after an additional delay Tdelay. If the voltage later rises above reconnection voltage (Vrecon) and stays for more than Trecon seconds, the model ramps the FracOn back up over Tramp to (1 - Fcease + Fcease x Frecon). Frecon is the fraction of the ceased load that reconnects. The model also accounts for timer resets and voltage drops during ramping.

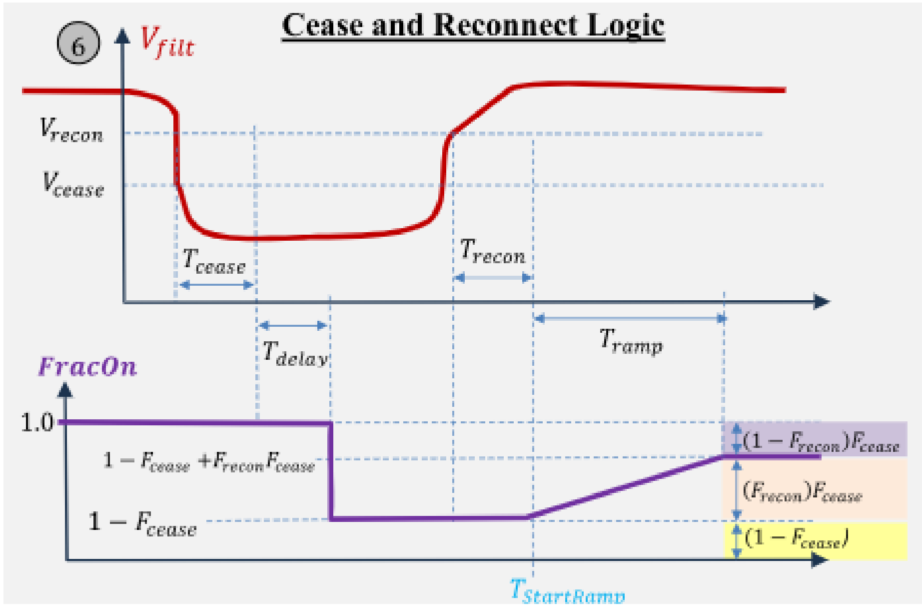


Figure 8. PERC1 model “FracOn” logic [15]

NATF Practices

6.1 Work with equipment vendors to obtain validated models of UPS systems, cooling motors, and other critical components. Generic assumptions can mask important dynamics.

6.2 Static load models are insufficient. At a minimum, the composite load model (CMLD) should be used for modeling large datacentric loads to allow dynamic studies of mechanically driven loads.

6.3 Utilize an advanced model such as Repurposed ISO-NE EV Model or the emerging PERC1 model to allow modeling ceasing and reconnection of large datacentric loads to evaluate voltage and frequency ride-through capabilities.

NATF Superior Practices

6.4 This superior practice redacted in open distribution version of the document.

EMT Modeling

Electromagnetic transient (EMT) models allow more detailed modeling of large datacentric loads and their interactions with the grid, particularly during rapidly changing conditions. The level of detail in EMT models can vary, so model requirements should be specified while considering how the model will be used [17].

NATF Practices

6.5 Require interconnection customers to provide electromagnetic-transient (EMT) models developed by original equipment manufacturers for detailed modeling of large datacentric loads.

6.6 Consider the following potential study uses when specifying EMT model requirements [10]:

- Detailed ride-through evaluations

- Sub synchronous oscillation impacts
- High frequency power quality impacts
- Interactions with other grid assets with power electronics controls

6.7 Perform a validation and verification process for each EMT model using the following strategies [18]:

- Simulation studies
- Hardware-in-a-loop testing
- Field measurements
- Benchmarking actual events

6.8 As energy storage support can smooth out a range of load variation, the EMT model needs to capture the details of the energy storage system, from facility-level, longer duration, energy dense storage to rack level, shorter duration, power dense storage support that may be present to assist in riding through the grid disturbances.

Model Verification and Quality

Model verification involves reviewing documents, files, or model settings and using engineering judgment to evaluate whether they conform to expected values or model structure.

A model quality test is used to ensure that a simulation model is both accurate and reliable for power system studies. By running these tests, engineers can confirm that the model correctly represents real-world behavior of the datacenter load.

NATF Practices

6.9 Review submitted model documents, files, and parameters for appropriateness as compared to models verified and validated previously.

6.10 Utilize model quality checks as part of interconnection modeling requirements:

- User-settable control modes and settings are accessible and well-documented (e.g., protection, ramp rates, ride-through thresholds, dynamic active/reactive power controls).
- The model supports minimum simulation time step requirements and operates reliably across a range of time steps.
- Flags and setpoint signals are provided for user debugging.
- Models initialize correctly without errors.
- The model complies with software version, dynamic link library (DLL), and compiler compatibility requirements.

> Different dynamic models (i.e., positive sequence standard library model, positive sequence UDM, and EMT model) should match as much as practical given potential software differences. Simulations can be performed (when feasible) to demonstrate agreement among various models.

NATF Practices

6.11 Perform a qualitative review of the dynamic response by applying disturbances across models. Characteristics to check include:

- The models generally react similarly when subjected to voltage, frequency, and phase angle jump tests
- Stability performance (damping, oscillatory behavior, etc.) generally matches and any anomalies can be explained thoroughly
- Post-event steady-state conditions match
- The responses of the models overlay on top of one another with sufficient precision

7. Interconnection Studies

System Impact Studies

Interconnection studies can include a wide range of evaluations and analyses to determine system limitations and identify system improvements associated with the interconnection request. The complexity and depth of analysis should be driven by the maturity of the interconnection request. Together, these individual studies comprise the System Impact Study (SIS).

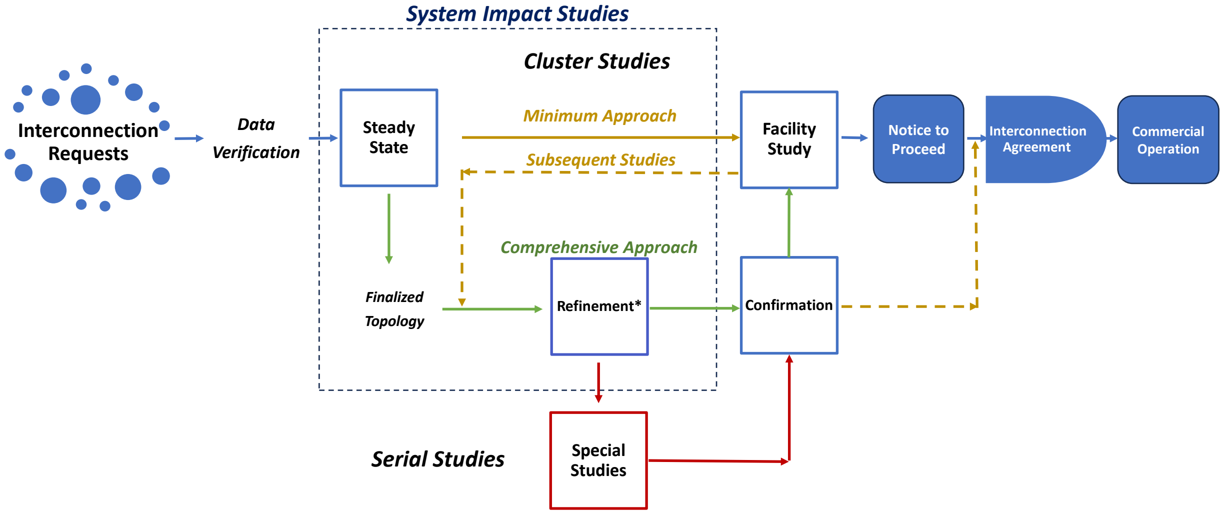
Before formally submitting interconnection requests, potential interconnection customers may seek cursory reviews or screening studies as described in section 5 above.

A flow diagram of the types and potential sequences of specific studies for the SIS is shown below in Figure 9. This diagram shows both minimal (shown in yellow) and comprehensive (shown in green) approaches to completing necessary studies prior to commercial operation. The dual approach is intended to reflect practical ways to respond to the magnitude and frequency of requests while still completing required studies. Future actions from FERC and/or NERC may necessitate adjustments to this recommended approach.

After data verification (see section 4), interconnection requests that have met technical, financial, and project requirements are evaluated using steady state analysis. In the comprehensive approach, any necessary changes to system topology identified during steady state analysis are used as the basis for refinement studies which include short circuit, dynamic, and power quality analyses. Also at this stage, screening criteria may be applied to determine if EMT analysis and/or additional special studies are needed. If so, these analyses are completed on an individual interconnection request basis independent of the cluster. Study results are re-examined to determine if triggers for re-study have been met before proceeding to Facility Study.

In some cases, TPs and PCs may be forced to proceed directly to Facility Study after completion of the steady-state assessment. This approach can be successful provided all required studies are still completed prior to interconnection agreement.

Details for each of the studies in the block diagram are covered in subsequent sections.



**Refinement studies may include Short Circuit, Dynamic Stability, Power Quality, Frequency Response, Voltage Stability, Power Transfer, and EMT Screening*

Figure 9. Study phases for large datacentric loads

Steady State

Steady state analysis is used to study how a power system behaves under normal and contingent operational conditions once transients have settled. It is performed to identify thermal loading, voltage exceedances, and scenarios causing voltage collapse or case divergence resulting from the addition of the requested load, as well as mitigations to these violations, if required.

NATF Practices

7.1 Case selection and development

7.1.1 Base cases are developed to represent all planning projects over the specified time horizon (nominally 10 years) at the time the large datacentric load will enter into service.

> Base cases are the starting point, representing the system as is, and are used to evaluate the interconnection request. These cases can start from regional development (i.e., Multiregional Modeling Working Group [MMWG]) and then be further enhanced with more detailed models for the local system being studied.

7.1.2 Study cases should be selected from the base cases to adequately evaluate the impact of the large datacentric load interconnection on the system. The TO will determine which years (normally up to three) may be used to perform the system impact studies. The determination will be based on the large datacentric load aggregation schedule and other factors such as the requested in-service date of the interconnecting load, in-service dates for nearby loads or generation, the load aggregation of the interconnecting load or other nearby loads, in-service dates for projects with the potential to impact the interconnecting load, or standard near-term or long-term study cases being used for other evaluations.

7.1.3 Sensitivity analysis may be considered to study the impact of the interconnecting load for various system conditions.

7.1.4 Transmission, generation, and load assumptions are defined for study cases and are generally derived from base case assumptions, load forecasting assumptions, and published or internal generation, transmission, and distribution plans.

7.2 Perform steady state thermal and voltage assessments considering the following:

7.2.1 Selected contingencies

Studies are performed for normal and contingency conditions in accordance with NERC Reliability Standard TPL-001 [19], in which contingencies are classified as P0 through P7. Thermal and voltage guidelines should not be violated for either normal operations or under the loss of system elements. Specific contingencies to consider for large datacentric loads include:

- All equipment in service (P0)

  Ensure all equipment remains within continuous operating limits with all equipment in service.

- Single credible contingencies (P1 and P7)

Ensure no violations for single element contingencies, multiple elements with common protective equipment, and multiple elements on shared structures. Outages of multiple lines sharing structures for one or more miles must be evaluated as P7 events for the TPL-001 standard, but individual practice may be more restrictive.

- Nearby bus contingencies (P2, P4) and stuck breaker contingencies (P4)
- Failure of non-redundant protection equipment (P5)
- Initial element out of service events (P3, P6)
- TPL-001 P3 and P6 events evaluate the system performance for a continuous operation and single contingency events after an initial outage condition. Generally, an initial event is simulated and reasonable operational actions, including switching equipment or re-dispatching generation, may be taken to bring loading and voltage within continuous operating limits, assuming they have not exceeded emergency operating limits, and to prepare for second level outages.
- Best practice generally involves simulating all initial and secondary outages. If violations are observed, a subset of initial outage conditions resulting in violations are generated. Cases simulating those initial outages can be created with operational actions applied and documented. Second level outages are then simulated for the initial outage cases with adjustments to confirm all violations can be mitigated.
- Engineering judgement should be used to determine whether to study P3 and P6 events and will be based on the location and voltage of the interconnecting load, load and generation, and local planning criteria. Initial and second level outages may include all single contingency events or a more limited set of contingencies, such as nearby generation, transmission lines or transformers within a certain proximity to the load, or based on the voltage of the equipment or inclusion in the BES. For example, a set of initial outages could be limited to BES equipment within five buses of the interconnecting load followed by simulation of all P1 events as second level contingencies.
- Depending on the study requirements and available time and computing power, a DC load flow solution could be used for screening studies or as a tool to identify potential issues for further study, which could include a DC solution with AC verification for loading above a set criteria or a smaller set of initial or second level events studied using a full AC load flow solution.
- Extreme events, including those defined by NERC [19]
- Although NERC TPL-001 does not require a corrective action plan for violations caused by extreme events, study is required to identify issues which may need to be addressed. Individual entities may choose to study all extreme events or certain events, such as the loss of a common corridor or all common corridors, based on their planning criteria. This may be necessary to identify mitigations that could be the responsibility of the interconnecting customer.
- Unintentional load loss of the load of an entire data center (or groupings of loads)

7.2.2 Data center load loss

While TPL-001 considers the loss of a large load or major load center to be an extreme event, recent events indicate the real possibility of one or more large datacentric loads disconnecting from the system. Therefore, it is recommended that the loss of a large load be considered as a credible event when studying the load and appropriate mitigations be put in place. In particular, it may be necessary to study these types of events during off-peak, low load, or low generation conditions to adequately assess the impact of the loss of load. Events to be simulated could include, but are not limited to, the loss of the load being studied, the loss of all load at the interconnecting station or nearby stations, and the loss of the interconnecting load and other nearby loads as a single event.

The following criteria may be used to determine the need to simulate data center loss of load events:

- Load size
- Proximity to other large loads
- Voltage level
- System topology in terms of the number of loads, the number of stations, and the number of transmission lines involved in the interconnection. This could involve evaluating the amount of load that might be dropped by N-1-1 contingency if there are a limited number of transmission connections.
- Data center process response to individual contingencies (some data centers may transfer to backup in their entirety upon partial loss of power to a subset of the facility load).
- New or existing substations serving large datacentric loads or large load additions may have significant concentrated load or generation facilities and multiple connections to other parts of the transmission system. Therefore, testing for the loss of a substation during interconnection studies could be a prudent approach to ensure adequate security enhancements are included at the time of construction if loss of the entire substation results in instability, uncontrolled separation, cascading, or the violation of other local risk assessment criteria.
- More stringent criteria may be set by the TO’s local planning guidelines.

7.2.3 Monitored thermal criteria

- Lines and transformers should not exceed continuous ratings during normal operation and should not exceed emergency ratings post-contingency. Seasonal ratings being monitored, if applicable, should be chosen based on study cases. In some cases, mitigations, such as operational switching or generation redispatch, must be available to bring ratings below continuous limits within a certain time period following a contingency.
- Selection of the areas or zones and voltage levels of lines and transformers being monitored should be chosen to capture equipment within close electrical proximity to the load being studied or with the potential to be affected based on the load location and contingencies chosen for study.

- If distribution factors are available, a distribution factor cutoff may be chosen as a means of determining whether the interconnecting load being studied is responsible for new thermal violations.

7.2.4 Monitored voltage criteria

- In general, bus voltages should remain within continuous operating limits during normal operation and should not exceed emergency operating limits post-contingency. Local criteria may have several emergency operating limits based on the contingency type or may have more restrictive limits at certain buses. Local criteria may also require mitigations, such as manual or automatic reactive device switching, operational switching, or generation adjustments to be available to bring post-contingency voltage within normal operating limits within a certain time period following a contingency.
- Selection of the areas or zones and voltage levels of buses being monitored should be chosen to capture buses within close electrical proximity to the load being studied or with the potential to be affected based on the load location and contingencies chosen for study.

7.2.5 Modes of analysis

- Comparison of pre-project and post-project cases

  A straightforward approach to studying the impacts of an interconnecting load is to model the load in each study case (base cases and sensitivity cases) at the requested load level and interconnection point. Generation is also increased to support the load. Actual generation adjustments will be determined on a case-by-case basis. In some situations, it may be preferred to increase all generation slightly throughout a defined area. Or specific or generic generation may be added at a local hub. In other cases, because known generators will be supplying the load or as a means of simulating stressed conditions, certain specific generation may be added or adjusted.

  For each study case, the pre-project and post-project cases are examined and new thermal or voltage violations are identified. These are then examined to determine whether the load addition is responsible for mitigating the violation. If needed, mitigations are studied in all post-project cases to ensure all violations are mitigated and no new issues are created.

- Transfer limit analysis

  In some studies, a transfer limit analysis may be beneficial to determine the load limit that can be supported prior to upgrades being required. Although this may be performed by examining results or through creation of several cases manually or by use of a script, certain software packages include tools to scale generation and load until thermal or voltage limits are identified.

  Transfer limit analysis may be useful for screening studies but can be useful in a SIS to determine what portion of the full load request can be supported prior to certain system upgrades that may not be able to be completed in the timeframe being requested by the customer.

- Evaluation of load serving limits

  Local systems may have certain criteria to limit load being connected to a single POI beyond those identified by power flow studies. These could include but aren't limited to a MW limit connected at a single substation, a MW limit on a radial transmission line, a MW limit a single substation requiring three or more sources, or a limit within a group of stations with a limited number of sources. Limits will generally be defined for reliability or based on operational criteria.

  Evaluation of these criteria will generally require a manual examination of the system, but some software may report load loss for certain events.

Short Circuit Analysis

NATF Practices

7.3 Perform short circuit assessments to ensure fault currents do not exceed a set percentage of the breaker's rating as defined by the TO's local planning criteria, identify the need for high fault current mitigations, and study those mitigations, if required. Consider the following fault conditions for each breaker evaluation:

- Single phase-to-ground
- Three phase-to-ground
- Double line-to-ground, in certain instances
- Fault resistance assumed to be zero
- Location of fault assumed to be at terminals of the breaker in question
- All elements in service as planned
- All breakers at a bus in service
- Breakers taken out, one at a time
- Line mutual impedance included
- All generation online
- Adjacent system fault contributions included
- Linear network solution used to determine the pre-fault voltage

7.4 At minimum, the following scenarios should be evaluated when performing short circuit assessments:

- System prior to the addition of the large load interconnection
- System with the large load interconnection and if applicable, system upgrades and collocated generation.
- System upgrades include new facilities identified through steady state, dynamic stability, and other analysis performed for the large load interconnection studies.
- Collocated generation is assumed to be generation directly associated with the large load being interconnected and connected in close proximity or behind the meter. The short-circuit

contribution from a collocated generator should not be double counted in the total fault current if that generator is represented explicitly by a separate model in the studies.

- Determine the impact of an interconnection by comparing the short circuit fault currents between the post-project and pre-project cases for the interconnecting bus, buses directly adjacent to the interconnection or assigned upgrades, and other nearby buses, defined by electrical connectivity or increase in fault current as a result of the project. It may also be prudent to monitor fault current at area buses known to have fault current within a set percentage of breaker interrupting capability.

7.5 The following may be used as a guide for assigning responsibility to the interconnecting customer if criteria are not already established by the transmission owner:

- Buses with breaker duties exceeding 95% of the interrupting capabilities as a direct result of the project.
- Buses with breaker duties increased by 2% of the interrupting capability as a direct result of the project.
- In situations where fault current exceeds criteria, mitigations should be identified. If mitigations involve changes in line impedance, such as series reactor additions, or changes in system topology, such as bus splits or line reconfigurations, update steady state and dynamic stability evaluations, and other necessary power flow evaluations, with short circuit mitigations included.

7.6 Short circuit studies should also include screening for weak system conditions, including calculation of short circuit ratio (SCR) during outage conditions as a screening tool for conditions that may require EMT evaluations or other special studies. Generally, an SCR value of 2 or less indicates a weak system with potential for sub-synchronous interactions.

7.7 If needed for protection studies or other special studies, obtain minimum fault currents during weak system conditions and with the customer online. These are normally obtained by simulating a weak system with equipment out of service and with nearby and collocated generation offline.

Dynamic Stability Analysis

After topological upgrades to the transmission system have been identified and modeled in the steady state portion of the interconnection study, this updated model becomes the basis for dynamic stability analyses. The stability of the TO’s system and neighboring systems must be maintained for the contingencies specified by NERC [19] or more stringent criteria as set by the TO’s local planning criteria.

NATF Practices

7.8 Update dynamic data files to include dynamic models provided by the interconnection customer(s). If the interconnection customer(s) does not provide dynamic models, the utility may choose best available models (see section 5) given available data.

7.9 Create a process for identifying the subset of contingencies that may have the most impact on transient stability for the BPS as required by NERC [19] or more stringent criteria.

7.10 If utilizing a cluster approach, include dynamic models of all projects to be considered in the study, using the following as guide:

- Identify at least two stability planning cases for evaluation.
- Perform dynamic stability analysis for each case.
- Analyze and compare the results to determine the impact of the interconnecting queue on the transmission system.

7.11 Perform dynamic stability assessments focused on the following topics [10]:

- Angular stability impact on nearby synchronous generation
- Synchronism of all generation within the interconnected system
- Impacts on stability-limited transfer paths (evaluate maximum path ratings after datacentric load interconnection)
- Transient voltage recovery and stability (may overlap with Voltage Stability Analysis)
- Large load ride-through and dynamic performance assessment (may overlap with Frequency Response)
- Impacts on local and inter-area oscillations using positive sequence (may not be required for every interconnection)

7.12 Perform dynamic stability assessments considering the following criteria [20]:

- Adhere to dynamic stability requirements in the latest version of TPL-001 [19]
- Adhere to regional or local dynamic stability requirements as applicable
- Ensure power and voltage oscillations are damped according to regional or local requirements, as applicable
- Both power and voltage oscillations should be considered
- Damping may need to be assessed with a technique to determine the oscillation meets certain damping performance criteria; such methods include, but are not limited to:
    - Visual plot inspection
    - Successive positive peak ratio (SPPR)
    - Modal decomposition
    - Eigenvector analysis
- New interconnections should not cause poorly damped oscillations that, in some cases, may extend beyond 30 seconds.
- Ensure the new interconnection(s) does not impact existing generator stability limits
- Evaluate post-fault recovery times for loads against system or RTO requirements (system dependent)

- If a result from the study-case violates any of the criteria, the base case transient stability analysis should be run for comparison to determine if the issue was pre-existing or caused by the interconnection of the project.

Power Quality Studies

Large datacentric loads are emerging as potential contributors to power quality disturbances on the electrical system. Evaluating the risk that the proposed load may cause electrical system power quality parameters to exceed established limits as part of the interconnection study enables power quality mitigation solutions to be incorporated into the detailed facility design. This section discusses typical power quality analyses that may be performed at this stage. The power quality phenomena considered are harmonic distortion, rms voltage variations, and voltage unbalance.

The ability of the system to supply short circuit current at the POI is a crucial parameter for all power quality analyses. It is important to consider realistic system conditions when selecting short circuit current values to be used in the studies.

NATF Practices

7.13 Consider all-ties-closed and feasible system contingencies.

7.14 Use conservative generation dispatch profiles including the case where local synchronous generation is unavailable.

7.15 Perform power quality studies in accordance with the most recent revision of following commonly adopted standards:

- IEEE Std 519 – IEEE Standard for Harmonic Control in Electric Power Systems [21]
- IEEE Std 1159 – IEEE Recommended Practice for Monitoring Electric Power Quality [22]
- IEEE Std 1453 – IEEE Standard for Measurement and Limits of Voltage Fluctuations and Associated Light Flicker on AC Power Systems [23]
- IEC 61000-4 Series – Power Quality Measurement Methods [24]
- Applicable utility interconnection and tariff requirements

Harmonic Load Flow Study

Steady-state harmonic voltage and current distortion introduced by nonlinear loads should be evaluated using harmonic load flow studies. The scope of the analysis evaluates:

- The individual harmonic voltage and current magnitudes
- Calculates the total harmonic distortion at the point of common coupling (PCC)
- Assesses the harmonic contribution of the new load

NATF Practices

7.16 Evaluate the harmonic current spectrum submitted by the prospective load and compare with the harmonic current distortion limits established in IEEE 519 for the proposed interconnection location.

7.17 Evaluate existing background voltage harmonics present at the proposed POI and the capacity of the electrical system to absorb the anticipated additional harmonics produced by the datacentric load while remaining below the IEEE 519 voltage distortion limits.

RMS Voltage Variation and Flicker Study

Large datacentric loads may produce voltage variations at the POI that may be evaluated against the light flicker and rapid voltage change planning limits established in IEEE 1453.

NATF Practices

7.18 Evaluate the expected rapid voltage change (RVC) produced at the PCC with the utility by infrequent load events such as large power transformer energization and compare with IEEE 1453 planning limits. If detailed magnetization data for the actual transformers to be installed is unavailable at the interconnection study stage, a screening study may be performed with generic data to identify the risk of RVC exceeding planning limits. This enables RVC mitigation to be incorporated into the facility detailed design.

7.19 Evaluate the RVC at the POI for infrequent demand step-changes for all system contingencies and compare with established planning limits.

7.20 Evaluate the magnitude and frequency of voltage variations expected to be produced by rapidly fluctuating datacentric loads, such as AI learning loads, and compare with established flicker perceptibility curves included in IEEE 1453.

Voltage Sags, Swells, and Transient Events

Datacentric loads are known to be sensitive to power quality phenomena such as voltage sags, swells, and transients as defined in IEEE 1159. These events may occur on the power system due to faults, switching, or load activities, such as starting large motors. This section describes analyses that may be completed in the interconnection study phase to determine the susceptibility of the proposed POI to these events and identify event mitigation strategies.

NATF Practices

7.21 Evaluate the vulnerability of the proposed POI to voltage sags caused by faults on the interconnecting transmission or distribution system(s) to ensure the electrical environment is compatible with the datacentric load.

7.22 Perform an area of vulnerability (AOV) study to establish the line-miles of exposure for which a fault on the electrical system will cause a voltage sag at the datacentric load POI.

7.23 Review historical fault data for lines within the AOV of the proposed POI to enable identification of required event mitigation. Examples of possible mitigation actions include insulator replacements, lightning arrester installation, or wildlife mitigation.

7.24 Evaluate the exposure of the POI to switching transients that may disrupt datacentric load operations. For example, high voltage capacitor bank switching near the POI may produce problematic voltage transients. If identified during the screening study, mitigation such as adding pre-insertion resistance to the capacitor bank switching may be planned.

Frequency Response

Frequency Response studies are generally performed in support of two NERC standards – BAL-003 [25] and PRC-006 [26] – with distinct purposes and goals. While these studies have not traditionally been considered for evaluation during interconnection requests, the addition of IBRs and large datacentric loads is changing the characteristics of the transmission system, which may necessitate studies occurring on a more frequent basis to address both purposes.

BAL-003 requires "sufficient Frequency Response from the Balancing Authority (BA) to maintain Interconnection Frequency within predefined bounds…until the frequency is restored to its scheduled value [25]." The standard ensures BAs provide Frequency Response Measure (FRM) equal to or more negative than the Frequency Response Obligation (FRO). In support of BAL-003, NERC issues "Frequency Response Annual Analysis" to identify allowable generation loss on an interconnection basis. This study defines the Resource Loss Protection Criteria (RPLC) for a given interconnection based on the two largest potential resource losses in an interconnection that may drive frequency downward toward unacceptable levels [27]. The loss of large datacentric loads that approach the RPLC in MW for a given interconnection – which in 2025 range from 2000 MW for the Quebec Interconnection (QI) to 3875 MW for the Eastern Interconnection (EI) - may merit individual frequency response studies due to potential system frequency increases. Additionally, large datacentric loads that have oscillatory operational characteristics (e.g., AI training) may also necessitate additional frequency response studies.

NATF Practices

Assess system impact of large datacentric loads to evaluate further frequency response study needs based on load size, location, or other operational impacts.

7.25 Assess system impact of large datacentric loads to evaluate further frequency response study needs based on load size, location, or other operational impacts. On-site non-emergency generation capabilities should be factored into these assessments.

7.26 Create a screening process to determine when individual (rather than system) frequency response studies are required that considers the following:

- System impedance or short circuit ratio
- If oscillation frequencies are near known resonance modes for the relevant interconnection
- If load loss is greater than or equal to the largest generator contingency within a BA
- If individual or total cluster load exceeds either 1000 MW or a significant percentage of the RPLC for the relevant interconnection as determined by subsequent studies or engineering judgement.

7.27 For those large datacentric loads where additional studies are performed, the following items provide a guide if utilizing a cluster approach to determine the relative impact of each interconnection request:

- Perform frequency response study for each interconnection request as applicable
- Analyze and compare the results to determine the impact of the interconnecting queue on the Transmission System.

By contrast, the purpose of PRC-006 is to "establish design and documentation requirements for automatic underfrequency load shedding (UFLS) programs to arrest declining frequency, assist recovery of frequency following underfrequency events and provide last resort system preservation measures [26]." This standard applies to Planning Coordinators plus TOs, DPs, or others that are responsible for the ownership, operation, or control of UFLS equipment. The standard requires establishment and maintenance of a UFLS database which is updated at least once per calendar year with no more than 15 months between maintenance activities.

NATF Practices

7.28 Interconnection study teams should inform UFLS program administrators of load additions and the potential for the significant changes in load shed calculations. The size of the load that could be interrupted relative to the system to be islanded should be considered as a factor for additional UFLS studies. The interruptible nature of loads should also be considered for UFLS program impacts.

Voltage Stability Analysis

Voltage stability refers to the ability to maintain system voltage so that both power and voltage are controllable [7]. Voltage stability analysis is comprised of a series of studies to evaluate the voltage stability impacts from potential interconnection studies for normal and post-contingency system conditions.

Steady State Analysis

A steady-state voltage analysis evaluates system compliance with steady-state voltage criteria by comparing pre- and post-project conditions.

NATF Practices

7.29 Start analysis with a pre-project system model to confirm there are no existing low or high bus voltage violations under normal or contingency conditions.

7.30 Verify that voltage deviations resulting from contingencies do not exceed established voltage deviation limits (typically ±10% depending on voltage class), commonly referred to as a delta V analysis.

7.31 Add the proposed load to the post-project model and repeat the analyses to determine whether the project addition causes violations of minimum, maximum, or voltage deviation criteria.

> If voltage violations are identified as a result of the project, recommendations for mitigation may include the addition of capacitors, reactors, or other fast-acting dynamic reactive devices.

High Voltage Transients from Load Rejection Events

Steady State High Voltage from Load Rejection Events

When large loads are added to the transmission system, voltage collapse could occur without any added support. Capacitor banks tend to be the preferred solution for steady state low voltage issues. This introduces an operational scenario where capacitors are needed pre-contingency to solve for low voltage constraints, but they could also drive high voltage constraints for load rejection. FACTs devices solve this issue, but they are converter-driven and have ride-through constraints that must be met for load rejection.

High Voltage Transients from Load Rejection Events

Sudden tripping of large load centers can cause short-duration high-voltage transients due to abrupt reductions in real and reactive power demand. EMT studies may be performed to evaluate partial and total data center load rejection under faulted and non-faulted conditions with an area dynamic reactive resource out of service (depicting a maintenance outage). If there are any area cap banks, these should also be switched into service. Studies need to show that resulting voltage excursions are brief and remain within applicable temporary overvoltage and insulation coordination limits. The TOV should also not result in tripping of any FACTs or area generation.

Post-Transient Voltage Stability

PV Analysis

One application of PV analysis is to increase active power flows (i.e., MW) from a source location (e.g., a regional power market) to a sink location (e.g., a large data center interconnection) and observe how quickly voltage decreases in the sink location. This method can be used to identify areas of potential voltage collapse. Active power transfers require VARs to support the flow of power. However, VARs inherently do not travel as easily as active power. Therefore, as the electrical distance of a power transfer increases, VAR losses increase significantly when compared to MW losses. Increased VAR losses consume both dynamic (e.g., generator) and static (e.g., capacitor bank) resources and can lead to, or worsen, voltage depression.

NATF Practices

7.32 Perform PV studies by increasing generation in the source area along with load in the sink area and recording the voltage at the sink bus(es) at each increment in generation.

> At some point, it is possible for an increment in source generation to result in a decrement of sink load. This is known as the Nose Point (a.k.a., Knee Point, or Voltage Collapse Point). The concept of a PV curve and identifying voltage collapse at a transmission bus is provided visually in Figure 10.

7.33 Identify an area susceptible to voltage collapse by power flow contingency analysis.

> Cases that fail to converge to a solution or that exhibit large post-transient voltage deviations are typically in or near a voltage unstable operating point, respectively. If the power flow program has the feature that can monitor dV/dQ from the Jacobian matrix during the P-V run, these quantities can provide information on the buses where the collapse will begin.

7.34 Identify the weakest bus that has the largest rate of change of the dV/dQ before collapse (i.e., the “nose”).

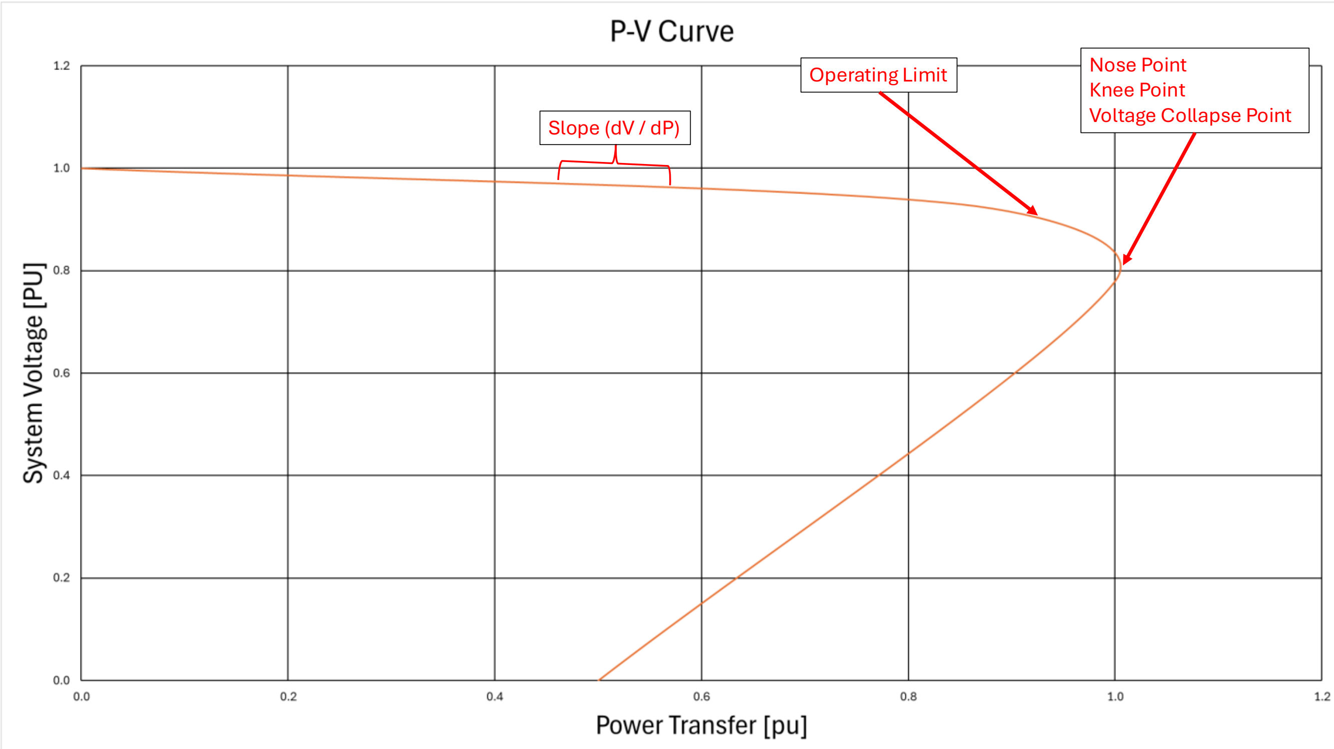


Figure 10. P-V curve with points/quantities of interest

QV Analysis

QV analysis is an assessment of how stable voltage is from a VAR standpoint at a single transmission bus. A QV study consists of three primary aspects:

- The Nose Point (a.k.a. Knee Point, or Voltage Collapse Point) - the voltage at which voltage collapse occurs.
- Reactive power margin - the quantity of VARs needed to prevent voltage collapse.
- If the minimum point of the V-Q curve is above the horizontal axis, the system is reactive power deficient. Additional infeed of reactive power is required to prevent a voltage collapse.
- If the critical point is below the horizontal axis, the system is stable with some reactive power margin.
- If reactive margin is a ≥ 0.0 quantity of VARs, the steady state voltage at the transmission location is unstable.
- Operating point - the voltage at which zero VARs are required to support voltage.

NATF Practices

7.35 Perform QV studies through the following actions:

- Selecting a transmission bus
- Turning off all capacitive shunt devices at the bus

- Applying a fictitious VAR source at the bus
- Recording the VAR requirements to achieve a set of voltage setpoints

> Typically, the first setpoint is high (e.g., 1.1 per unit) and the analysis steps voltage at the study bus down to lower setpoints. At a certain point, VARs will stop decreasing and begin to rise. This is known as the knee point. These characteristics are presented graphically in Figure 11.

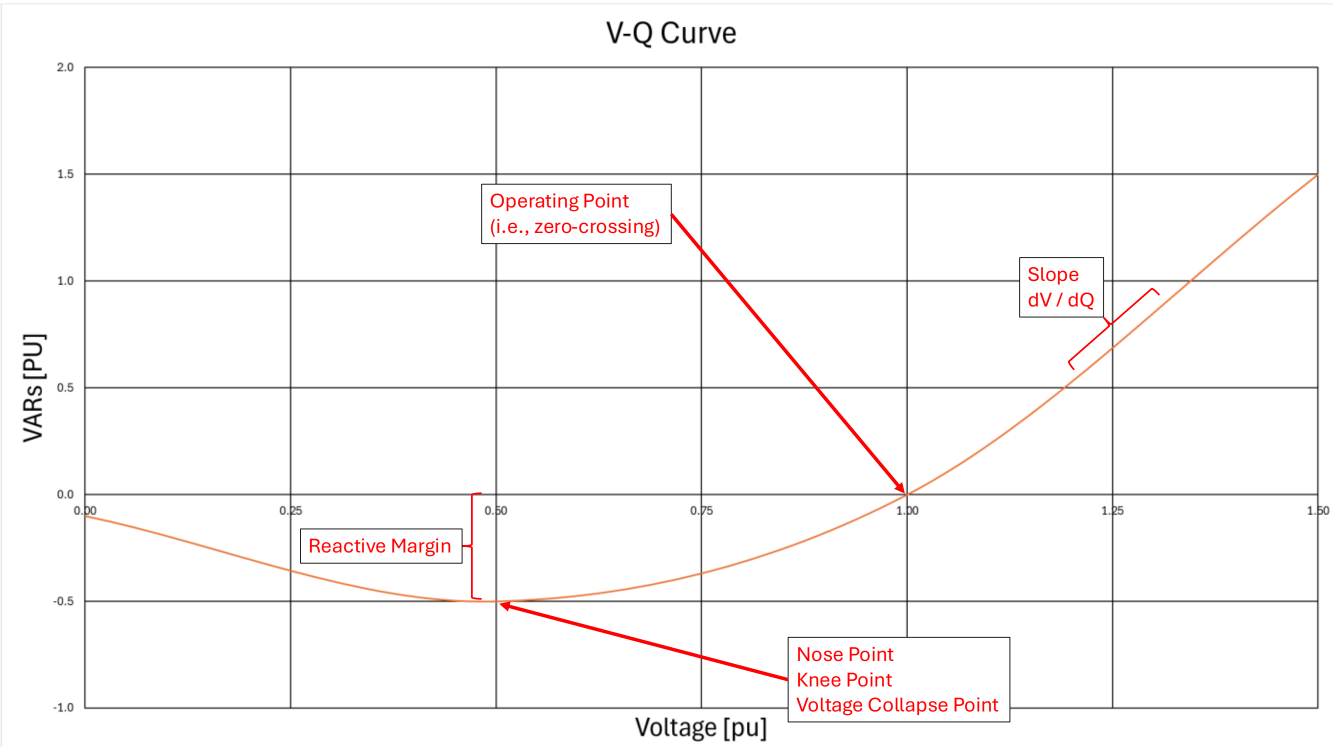


Figure 11. V-Q curve with points/quantities of interest

Transient Voltage Response Studies

The objective of transient voltage response studies is to evaluate load center behavior following transmission system–level faults and to assess the resulting voltage recovery performance after a contingency event. These studies ensure that the transmission system response is consistent with applicable performance requirements (e.g., NERC FAC-002 [28]and NERC TPL-001 [19]).

Transient voltage response is influenced by power system equipment with inherent dynamic and time-constant characteristics, including transformer automatic load tap changers (LTCs), synchronous condensers (SCs), generator excitation systems, flexible AC transmission system (FACTS) devices, voltage-dependent loads, inverter-based resources operating in voltage-control mode, and automatically switched capacitor banks. These dynamics must be properly represented in transient voltage studies.

NATF Practices

7.36 Apply conservative modeling assumptions for power-electronic loads (e.g., data centers or cryptocurrency facilities) where voltage ride-through or trip protection settings are uncertain.

> Such loads are assumed to trip for voltage depressions below 0.75 per unit lasting 20 milliseconds and are assumed not to recover during the simulation.

7.37 Assess low-frequency voltage oscillations and their duration as an integral part of transient voltage response evaluation.

> Low-frequency voltage oscillations following a disturbance that do not exhibit sufficient damping within 30 seconds, defined as a damping ratio remaining below 3%, are considered unstable.

EMT Screening Criteria

The NERC Large Load Working Group (LLWG) is planning to develop guidelines in collaboration with the NERC EMT Working Group (EMTWG) for EMT studies for large loads. However, currently, there is no clear guideline on the conditions that can trigger the requirement to conduct EMT analysis for different scopes of large datacentric load interconnection studies starting from collocation, cloud-service providers to hyper-scalers with multi-GW facilities, or possible AI service applications. In the absence of current industry-wide guidance, TOs and PCs should establish EMT screening criteria based on system topology and engineering judgement.

NATF Practices

7.38 Establish an EMT model screening criteria that considers, at a minimum, the following:

- Low short circuit strength
- Proximity of generators and potential for sub-synchronous control interactions (SSCI)
- Proximity of critical loads and other critical BPS connections, such as high voltage direct current (HVDC) converters, series capacitors, and FACTS devices with power electronic controls

> If any of the criteria are met, a detailed EMT study may be needed for the interconnecting load.

Special Studies

A variety of additional, more specialized studies may be required depending on the specific characteristics of the interconnection requests, the topology of the network in that area, and the availability of necessary data. EMT analysis (if indicated as necessary through screening criteria) may be required to model transient behavior of loads and the corresponding impacts to other grid assets. Sub-synchronous oscillation (SSO) analyses are used to determine potential generator impacts and control interactions. Additional studies may also be required to determine reactive compensation requirements.

EMT Analysis

In recent times, increased emphasis has been given to studying the transient behavior of large loads like data centers, crypto mining facilities etc. One of the primary reasons being the impact of their characteristics on the North American regional grid in terms of large load drops [1] due to uncoordinated protection settings, and injection of power oscillations [29] in the sub-synchronous torsional and control interaction range.

7.39 Consider the following uses for EMT analysis when evaluating large datacentric loads during interconnection studies and impact studies [18]:

- Identification of any power quality issues, including harmonics and voltage flicker.
- Protection settings and coordination of fault current protective devices.
- Identification of control interaction between the large datacentric load and nearby devices (e.g., voltage regulator).
- Fault ride-through (FRT) studies
- Reactive power and frequency support (if co-located with onsite generation)
- System strength assessment and impact on load hosting capacity: Determining the dynamic VAR margin for buses where data centers are connected. Assessing the performance of co-location for providing dynamic voltage or frequency regulation.
- Study of large load interaction with torsional modes of nearby turbines, electrical resonance with series compensated transmission lines.
- Characterizing fault response of the data center with an EMT model of facility level architecture and assessing the achievable ride-through response.

Sub-Synchronous Oscillation (SSO) Studies

This study should be performed to evaluate the SSO risk introduced by a proposed data center load project. The scope and requirements of the study depend on the type of generation involved and are categorized as described below.

Applicable to Conventional Generation and Transmission Facilities

Turbine generators located near large datacentric loads may be exposed to sub-synchronous resonance (SSR) conditions and should be evaluated. SSR occurs when network natural frequencies below the fundamental frequency coincide with turbine-generator torsional-mode frequencies, potentially resulting in excessive mechanical stress and shaft failure.

SSR interactions between the turbine-generator and the power system are classified into the following categories based on interaction mechanisms:

- Induction generator effect (IGE)
- Torsional interaction (TI)
- Torque amplification (TA)

NATF Practices

7.40 Assess potential SSR risks for new generator installations near data center loads by performing studies to identify any TA or TI impacts on nearby generating units.

> Contact with the original equipment manufacturer (OEM) may be necessary to obtain the required data.

7.41 Identify potential concerns during an initial screening process using a frequency scanning study.

7.42 Perform a more detailed time-domain transient study to quantify potential damage and identify appropriate mitigation measures.

7.43 Require interconnection customers demonstrate that SSR studies have been conducted for all affected nearby generation units.

Applicable to Intermittent Renewable Generation and Transmission Facilities

Inverter-based generation facilities (power-electronic-based resources such as wind turbines and solar photovoltaic plants) located near load centers or points of interconnection (POI) may be exposed to sub-synchronous control interaction (SSCI) conditions and should be evaluated accordingly.

SSCI refers to interactions between power electronic controllers, or between power electronic controllers and series-compensated transmission lines, within the vicinity of the added load center facility. This will result in voltage or current amplifications and possible damage to the equipment.

NATF Practices

7.44 Conduct screening studies to determine whether the interconnection of the data center facility introduces any SSCI risks. The customer is required to provide detailed full transient models (not the average model) that accurately represent the data center's control systems.

7.45 Ensure modeling data required to conduct SSCI studies includes, but is not limited to, the following:

- Protection system models, including low voltage ride-through (LVRT) settings where applicable
- Transient models of load centers components
- Transient models of supplemental dynamic devices (including switchable shunts, STATCOMs, and SVCs), unless it can be demonstrated that such devices do not exacerbate sub-synchronous interactions

7.46 Require any identified SSTI or SSCI issues be mitigated by the interconnection customer prior to interconnection approval.

7.47 Re-evaluate studies for any changes in transmission system topology within the vicinity of the load center facility.

Reactive Compensation Studies

The large increase in the number of data centers under development will have several impacts on the transmission system that require reactive resources, which could be either capacitors or STATCOMS. A static synchronous compensator (STATCOM) is a dynamic reactive device that can be used to provide a temporary injection/absorption of VARs to mitigate transient issues such as voltage flicker, harmonic distortion, or fault-induced delayed voltage recovery (FIDVR).

A great deal of study work is required to characterize a STATCOM appropriately for specification to a vendor. Standardizing specific STATCOM sizes per system has both planning and maintenance benefits.

Generation resources – both synchronous and inverter-based - will vary by system and have differing reactive support capabilities. If generation resources are at or near their reactive limits, the only other sources of fast, dynamic reactive capability are FACTS devices like STATCOMs. Large data centers will need additional dynamic reactive support to support large, instantaneous changes in load, as will AI data centers.

NATF Practices

7.48 Develop a process to determine MW thresholds above which STATCOMS will be required based on facility power factor and load characteristics, voltage level, system topology, existing reactive margin, etc. for use in preliminary scoping efforts.

7.49 Develop a process to determine MW thresholds below which STATCOMS will not be required based on facility power factor and load characteristics, voltage level, system topology, existing reactive margin, etc. if conventional reactive support can meet system needs.

7.50 If detailed studies are deemed required for specifying a STATCOM, recommended steps and studies include:

- Need identification (power quality, FIDVR mitigation, etc.)
- Use case (local area or customer-specific mitigation)
- Feasible sites, i.e., one or more locations that:
    - Can accommodate the physical space requirements of a STATCOM.
    - Have adequate short circuit strength.
    - Are adequately connected to the rest of the network where issues are observed.
- STATCOM sizing for each feasible site.
- Dynamic stability studies are typically required to determine the required STATCOM size in MVAR.
- Depending on STATCOM application, power flow and/or electromagnetic transient studies may be required.
- Site selection (based on feasibility and sizing studies, one location is chosen to host the STATCOM).
- Network harmonic impedance scan at the chosen STATCOM site (determine potential harmonic resonances in the electrical network).
- Background power quality measurement (collect voltage/current harmonics and, if necessary, voltage flicker to support vendor studies).

Triggers for Re-study

Including a confirmation checkpoint in the system impact study process to reassess studies already performed before proceeding to Facility Study is prudent to ensure the latest information is utilized to determine interconnection scope.

NATF Practices

7.51 Evaluate latest information from interconnection customers to determine if studies need to be re-examined using the following criteria:

- Those items listed under "Qualified Change" section
- Change in percentages of computing/server loads from initial request
- Nearby system topology changes
- Project load schedule changes
- Cross-check opportunity with other projects in the cluster

Facilities Study

NATF Practices

7.52 Perform a facilities study or engineering assessment that produces preliminary cost estimates and tentative schedule for the design, construction, and commissioning of network upgrades and facilities required for the interconnection of the load based on the system impact study. The following items should be included in the scope of a facilities study [30]:

- Interconnection facilities that are directly required to support interconnection of the datacentric load (e.g., substation equipment, relays, controls, communications, metering, and switch house).
- Network upgrades assigned to the interconnection (stand-alone additions and modifications)
- Network upgrades allocated to the interconnection if part of a cluster
- Contingent facilities required to be completed before the interconnection can be placed in-service
- Other scopes of work as indicated by the system impact study

7.53 Ensure Facilities Study reports include the following:

- Summary of scope
- Conceptual cost estimates, accuracy band, and exclusions
- Preliminary milestone schedule for completion of TO work and dependencies
- Payment milestones from customers
- Assumptions and study limitations
- Monitoring requirements (PQ, PMU, etc.)
- Potential UFLS requirements

- Site, environmental, real estate, and permitting requirements
- Outage planning and constructability constraints
- Tariffs and regulatory references (either through inclusion or reference if posted publicly)
- Technical requirements and standards (either through inclusion or reference if posted publicly)

8. Interactions

Establishing and maintaining effective communication channels with customers, operational partners, stakeholders, and subject matter experts throughout the interconnection process facilitates prompt answers to potential issues and ensures all parties are aware of the status of the interconnection request.

Communications with Customers

Identifying the appropriate contacts for technical, business, and operational issues is key to efficient resolution of issues throughout the interconnection process.

NATF Practices

8.1 Establish points of contact for technical issues with the interconnection customer.

8.2 Establish points of contact for business and commercial issues with the interconnection customer.

8.3 Establish communications capabilities for operational issues to improve situational awareness through voice, SCADA or other communications platforms [2]. This includes both onsite and remote facility control centers (if applicable).

8.4 Establish a method for tracking communications and document submittals with customers throughout the interconnection process that is accessible to relevant organizations.

8.5 Establish cadence for periodic verification for points of contact.

Communications between TPs, PCs, and TOs

While organizational models vary from vertically integrated utilities to those that operate within ISO/RTOs, clear and effective communication between organizations that house the TP, PC, and TO functions – whether internal or external – is crucial for successful completion of the interconnection process.

NATF Practices

8.6 Establish which party has responsibility for communications with the interconnection customer.

8.7 Share relevant data with all parties directly involved in evaluating the interconnection request.

8.8 Establish a method for tracking communications and document submittals between TPs, PCs, and TOs throughout the interconnection process that is accessible to relevant organizations

8.9 Establish points of contact within the TP, PC, and TO to facilitate communication of the following:

- project updates and status changes
- issue resolution during the process
- study review process
- customer engagement

Cross Departmental Engagement and Collaboration

Successful and efficient execution of the interconnection process requires coordination across departments within an organization.

NATF Practices

8.10 Ensure relevant departments or functions are aware and appraised of interconnection status. These include but are not limited to the following:

- Transmission planning, modeling, and/or special studies
- Customer relations
- Communications/Public Affairs
- Industrial inquiries
- Interconnection (if dedicated department or group exists)
- Transmission lines
- Transmission substation
- Distribution design and construction (if applicable)
- Protection and control
- System operations
- Operator training
- Operations planning
- Legal and regulatory compliance
- Revenue metering
- Billing and accounting
- Rates and tariffs
- Project management
- Transmission construction
- Asset management
- Physical security

> Specific departments and business unit names may vary between organizations.

9. Related Documents

The following documents influence or relate to this document in some manner:

- "NATF Inverter-Based Resource Interconnection Lifecycle: Interconnection Requests and Studies Practices," North American Transmission Forum, 2025.

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Appendix 1: Large Datacentric Load Questionnaire – General Information

This document is located on www.natf.net/documents in the Resources section under the Planning and Modeling topic area.

Appendix 2: Large Datacentric Load Questionnaire – Technical Information

This document is located on www.natf.net/documents in the Resources section under the Planning and Modeling topic area.