NERC
NORTH AMERICAN ELECTRIC RELIABILITY CORPORATION

Assessment of Gaps in Existing Practices, Requirements, and Reliability Standards for Emerging Large Loads

NERC Large Loads Working Group White Paper

March 2026

RELIABILITY | RESILIENCE | SECURITY




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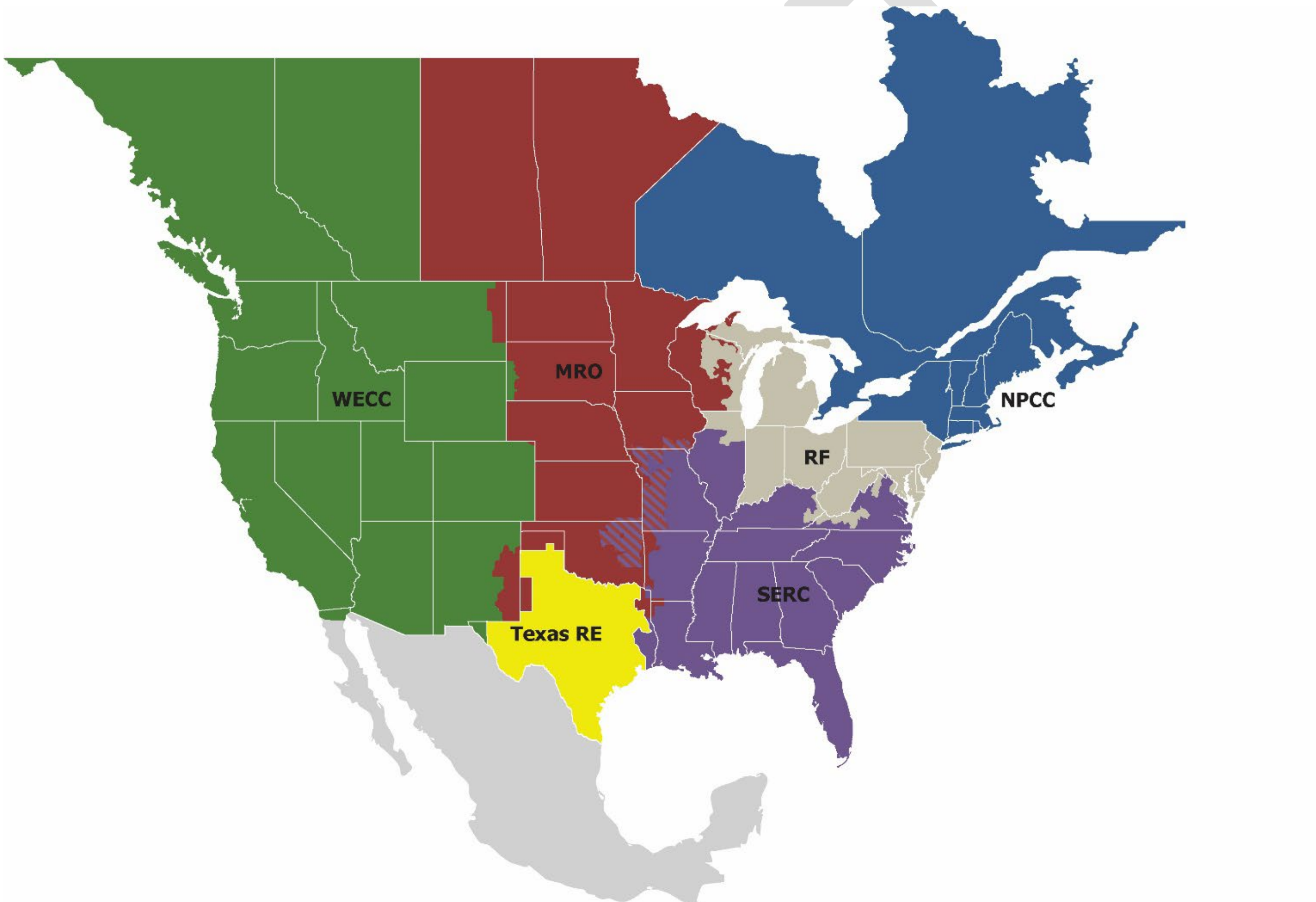
Preface

Electricity is a key component of the fabric of modern society and the Electric Reliability Organization (ERO) Enterprise serves to strengthen that fabric. The vision for the ERO Enterprise, which is comprised of NERC and the six Regional Entities, is a highly reliable, resilient, and secure North American bulk power system (BPS). Our mission is to assure the effective and efficient reduction of risks to the reliability and security of the grid.

Reliability | Resilience | Security
Because nearly 400 million citizens in North America are counting on us

The North American BPS is made up of six Regional Entities as shown on the map and in the corresponding table below. The multicolored area denotes overlap as some load-serving entities participate in one Regional Entity while associated Transmission Owners/Operators participate in another.



MRO	Midwest Reliability Organization
NPCC	Northeast Power Coordinating Council
RF	ReliabilityFirst
SERC	SERC Reliability Corporation
Texas RE	Texas Reliability Entity
WECC	WECC

Executive Summary

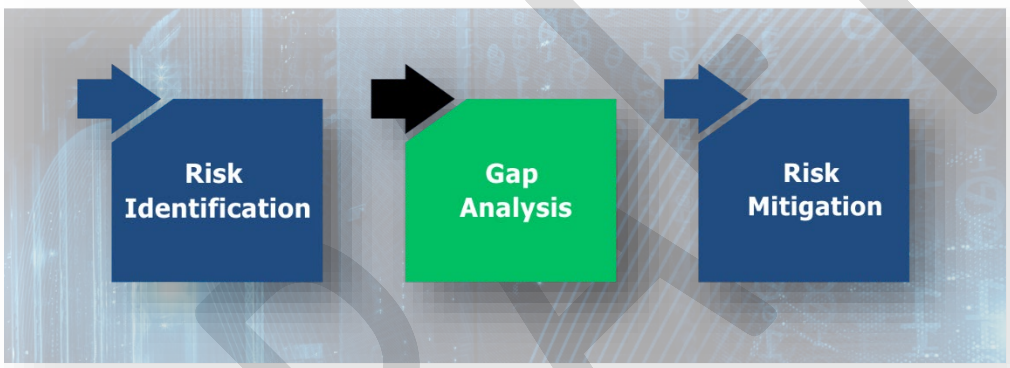
A New Challenge on the Horizon

As the North American electric system evolves, emerging large loads are challenging the reliability, resilience, and security of the North American bulk power system (BPS).[1] These large load facilities are rapidly increasing in number, scale, and operational complexity, creating challenges under existing NERC Reliability Standards, interconnection practices, and system planning assumptions that were not designed to account for their unique characteristics.

NERC's Response

Large load facilities are rapidly increasing in number, scale, and operational complexity

To respond to this evolving landscape, NERC commissioned the Large Loads Working Group (LLWG)[2] of NERC's Reliability and Security Technical Committee (RSTC) to identify potential gaps related to large load[3] integration in Reliability Standards, interconnection requirements, and Institute of Electrical and Electronics Engineers (IEEE) Standards,[4] as well as in utility practices like load forecasting and load modeling practices. This paper comes after previous work that outlined the [characteristics of large loads and identified the reliability risks] they may present to the BPS.



NERC's *Assessment of Gaps in Existing Practices, Requirements, and Reliability Standards for Emerging Large Loads* evaluates gaps related to the following:

- **Interconnection processes and requirements**
- **Planning and resource adequacy**
- **Balancing and operations**
- **Disturbance ride-through, stability, and power quality**
- **Security**
- **Resilience and event analysis**
- **Load modeling**

[1] Glossary of Terms Used in NERC Reliability Standards
[2] In December 2025, the Reliability and Security Technical Committee promoted the Large Loads Task Force to be a working group.
[3] See Chapter 1 for the definition of "large load" for this paper.
[4] IEEE Standards are voluntary and must be adopted by a governing body to become enforceable. By contrast, NERC Reliability Standards are developed for the purpose of becoming mandatory and enforceable on users, owners, and operators of the BPS in North America.

Furthermore, this white paper categorizes the risks to the BPS related to large loads to determine the appropriate mitigations.

> **…existing Reliability Standards and the existing processes and requirements related to BPS planning, operations, security, and other areas are inadequate to address the risks posed by emerging large loads**

Overall, this white paper finds that the existing Reliability Standards and the existing processes and requirements related to BPS planning, operations, security, and other areas are inadequate to address the risks posed by emerging large loads that are forecasted to make up a significant portion of the future grid. This inadequacy exists because the regulatory regime was established at a time when most significantly sized loads had different operating characteristics when compared to the data center or cryptocurrency mining and other emerging large loads currently seeking interconnection.

Building a Strong Foundation

This paper serves as a foundational step in updating industry practices to address the challenges of integrating large loads into the evolving electric grid. Alongside the Large Loads Task Force (LLTF) *Characteristics and Risks of Emerging Large Loads* white paper,[5] it performs Step 1 of the RSTC Standard Authorization Request (SAR) Process.[6] The RSTC or others may[7] consider developing SARs or other mitigating measures to mitigate the reliability gaps discussed in this paper.

Essential Insights: Key Reliability Recommendations

The following provides a summary of the LLWG recommendations based on the gaps assessed in this paper. The detailed list of recommendations can be found in the **Conclusion**.

- ✓ **Recommendation 1:** There are multiple high-impact risks to the BPS from large loads that NERC registered entities[8] cannot adequately address. The LLWG recommends that NERC pursue registration of a type of entity (or types of entities) that is able to perform specific functions to address the risks.[9]

- ✓ **Recommendation 2:** The LLWG and other groups should propose SARs to address the unmitigated risks to the BPS related to emerging large loads.

- ✓ **Recommendation 3:** The LLWG should identify potential mitigations to risks posed by emerging large loads through improvements to existing planning and operations processes and interconnection procedures for large loads as planned for the LLWG's work item titled *Reliability Guideline: Risk Mitigation for Emerging Large Loads*.

- ✓ **Recommendation 4:** Registered entities should coordinate and collaborate with large load entities and update their practices to address the gaps discussed in this paper.

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[5] Available here: White Paper Characteristics and Risks of Emerging Large Loads

[6] Available here: RSTC SAR Development Process clean Sept 20 2023.pdf

[7] *Ibid. See also*, the NERC Rules of Procedure regarding submittal of SARs.

[8] See NERC Rules of Procedure Appendix 5A and NERC Rules of Procedure Appendix 5B for more information on registered entities. Available here: Rules of Procedure

[9] The findings of the NERC Level 2 Alert: Large Load Interconnection, Study, Commissioning, and Operations, distributed on September 9, 2025, will likely help provide more information regarding the need to pursue registration of an entity type (or types of entities).

- ✓ **Recommendation 5:** To address the gaps discussed in this paper, Transmission Owners (TO) should coordinate with other registered entities as applicable to update their interconnection requirements; Planning Coordinators (PC) and Transmission Planners (TP) should update their interconnection study processes.

- ✓ **Recommendations 6-8:** The NERC Load Modeling Working Group should work to address the applicable gaps identified in this paper. Additionally, the Security Working Group and the System Protection and Control Working Group should further assess applicable gaps and propose mitigations to address the gaps.

- ✓ **Recommendations 9-10:** Federal and/or state regulators, as applicable, should consider the gaps identified in this paper and coordinate with utilities to assess whether incorporating additional interconnection requirements and/or studies are appropriate to reliably support integration of large loads. State regulators should work with regulated utilities to review how new loads and planned additional generation impact existing planning and risk assessment frameworks. States may need to adjust their resource adequacy criteria and/or work with their utilities on energy infrastructure expansion.

- ✓ **Recommendation 11:** Policymakers should review interactions between interconnection requirements, existing state regulations and planning processes, and regional grid operator requirements. Additionally, policymakers should work to better understand the full impact of large load integration in their jurisdiction, and review requirements for large load customers to provide operational data and information to TOs, TOPs, TPs, and other entities.

Chapter 1: Introduction to Emerging Large Load Gap Analysis

Intended Audience

This paper is intended for the following NERC registered entities, external entities, and broader groups:

- Planning Coordinators (PC)
- Resource Planners (RP)
- Transmission Planners (TP)
- Transmission Owners (TO)
- Transmission Operators (TOP)
- Distribution Providers (DP)
- Balancing Authorities (BA)
- Reliability Coordinators (RC)
- Large Load Developers, Owners, Operators, or Other Related Companies
- Generator Owners (GO)
- Generator Operators (GOP)
- Load-Serving Entities (LSE)
- Reliability and Security Technical Committee (RSTC) Subgroups
- FERC
- State Regulators and Other Regulatory Entities
- Consumer Advocates

This paper analyzes the gaps in existing practices,[10] requirements,[11] and NERC Reliability Standards related to emerging large loads and provides recommendations for addressing the gaps. Entities responsible for operating and planning the BPS should be aware of these gaps and work to address the gaps in their own practices and requirements to reliably plan and operate the BPS. This paper also identifies areas where potential gaps associated with emerging large loads require further assessment by related RSTC groups.

NERC Large Loads Task Force

The NERC LLWG aims to understand the reliability impacts that emerging large loads, such as data centers and other computational loads, large industrial loads, and hydrogen fuel plants, will have on the BPS. The LLTF has two primary phases identified in the NERC LLTF scope as follows:[12, 13]

- Phase 1: Identify unique characteristics and risks of large loads
- Phase 2: Identify gaps and potential risk mitigation

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[10] As NERC Reliability Standards are the minimum performance needed for BPS reliability, utilities have practices that extend beyond the NERC standards. These practices are often related to NERC standards but may extend beyond the standards.

[11] These requirements include interconnection requirements as well as IEEE standards

[12] LLTF Scope

[13] At the time of the writing of this white paper, a new scope for the working group has not yet been RSTC approved. In the interim, the LLWG has inherited the scope of the LLTF.

This paper completes the gap identification portion of Phase 2 of the LLTF scope. This paper, in conjunction with the planned reliability guideline, additionally addresses the mitigation identification portion of Phase 2 of the LLTF scope. The remaining portions of Phase 2 of the scope will be completed in future LLWG activities.

Large Load Definitions

As defined in the NERC LLTF *Characteristics and Risks of Emerging Large Loads* white paper,[14] the definition of "large load" for this paper is the following:

"Any commercial or industrial individual load facility or aggregation of load facilities at a single site behind one or more point(s) of interconnection that can pose reliability risks to the 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."

Regulatory updates could develop more specific definitions at a later date. On page 16 of NERC's comments submitted in response to FERC's Advance Notice of Proposed Rulemaking on potential reforms to enable the interconnection of large loads to the transmission system, NERC has provided an example timeline for addressing the issues related to the reliable integration of large loads onto the BPS. This example timeline includes filing NERC Rules of Procedure registry criteria changes, along with aligned standards glossary revisions, in Q1 2027. This timeline also includes drafting and filing NERC Reliability Standards during 2027.

More specific definitions could also differentiate within the large load category. The potential impact of several 100 MW loads may be less than the impact of a 500 MW load and may require different treatment. The emergence of gigawatt-scale loads may create exponential complications for study, planning and operations.

Additional definitions related to large load facilities for this paper are the following:

- **Data Center:** "…[A] physical room, building or facility that houses [information technology (IT)] infrastructure for building, running and delivering applications and services."[15]
  - Categories of data centers include traditional data centers, artificial intelligence (AI) training data centers, and AI inference data centers.[16]
- **AI Training:** "…[T]he creation and modification of an AI model and its associated model weights."[17]
- **AI Inference:** "…[T]he process of using a pre-trained AI model to generate output(s) based on new input."[18]
- **Cryptocurrency Mining Facility:** A physical facility housing IT infrastructure for performing cryptocurrency mining.
- **Cryptocurrency Mining:** "…[t]he process of verifying and recording transactions on a blockchain using advanced computing power."[19]

Background

According to NERC's 2025 *Long-Term Reliability Assessment* (LTRA), the aggregated summer peak demand forecast for the North American BPS is predicted to increase by over 224 GW over the 2026–2035 time frame; the aggregated winter peak demand forecast is predicted to increase by 245 GW over this same time frame. Overall, data centers

[14] Available here: White Paper Characteristics and Risks of Emerging Large Loads
[15] What Is a Data Center? | IBM
[16] White Paper Characteristics and Risks of Emerging Large Loads
[17] *Ibid.*
[18] *Ibid.*
[19] What is Cryptocurrency Mining & How Does it Work? - Crypto.com International

account for the majority of this demand increase, while cryptocurrency mining facilities are one of the primary demand drivers for this growth in two portions of the North American BPS.[20]

Changing Gaps

While the gaps in practices, requirements, and modeling identified in this paper were accurate when the content of this paper was initially being drafted, many utilities, entities in the large load industry, and others are working to address the gaps (e.g. by implementing ride-through requirements). Therefore, some of the requirements, practices, and modeling at the time of the publishing of this paper may be different than discussed in this paper.

[20] 2025 Long-Term Reliability Assessment

Chapter 2: Interconnection Processes and Requirements

Due to the complexity and risks that emerging large loads introduce to the BPS, large load interconnection requirements and energization processes must be designed to support grid reliability and incorporate any needs and requirements of the applicable TO, BA, RC, and other applicable entities. Without thorough system study, analysis, review, and approval processes, TOs may interconnect large loads with inadequate design and before operational readiness is ensured. The BPS impacts from emerging large loads can extend beyond the immediate system to which they are connected; they present performance implications of which neighboring systems need to be aware. This section discusses gaps and key issues in the interconnection of emerging large loads, including the lack of comprehensive study and performance requirements in the interconnection process, data sharing, and coordination and collaboration between large load entities, utilities and other entities.

On November 21, 2025, NERC submitted comments in response to FERC's Advance Notice of Proposed Rulemaking on potential reforms to enable the interconnection of large loads to the transmission system. NERC's filing emphasized the need for consistent visibility into new large loads, clear coordination requirements among entities, and robust planning processes that support reliability in a rapidly transforming grid environment. The LLWG supports FERC's examination of these issues in Docket No. RM26-4.

Gaps Related to Interconnection Processes

Because: (i) large loads have not been a focus under Reliability Standards for existing registered entities and (ii) neither large loads nor LSEs are registered entity functions under the NERC registry criteria, this white paper finds that the existing Reliability Standards and interconnection requirements do not adequately mitigate large loads' reliability impacts on the BPS.[21]

- For example, Reliability Standard FAC-001[22] requires TOs to establish interconnection requirements for generators as well as loads, and Reliability Standard FAC-002[23] requires TPs and PCs to study impacts and correct identified reliability risks; however, challenges have been observed with how the interconnection requirements used for generators and traditional loads apply to emerging large loads.
- Even though FAC-001 allows TOs to establish interconnection requirements for "end-user Facilities"[24] like large loads, the current interconnection requirements may not adequately identify the impacts on the BPS, and the requirements may lack clarity and specificity for the interconnection of large loads. The BPS impact from emerging large loads can be much greater than those of historical load additions.
  - A recent NERC report[25] on a large load event highlighted issues that are not adequately captured by existing TO interconnection requirements. Interconnection requirements may have gaps related areas such as voltage/frequency disturbance ride-through, sensitive protection settings, ramping, power quality, and oscillation.
- There are currently no NERC standards for model quality to ensure that the load models reflect the real-time behavior of large loads during system disturbances that cause frequency or voltage variations.[26] Large load entities are currently not directly obligated under existing NERC standards to provide data and timely updates or to maintain data accuracy and appropriate load models. Further discussion on model validation and model quality gaps can be found in **Chapter 7**.

[21] Based on specific facts and circumstances approximately 10 years ago, the LSE function was removed from the NERC Rules of Procedure. However, the role of this previous function may be able to be tailored to address large load risks.
[22] Available here: FAC-001-4
[23] Available here: FAC-002-4
[24] FAC-001-4
[25] Available here: Incident Review - Considering Simultaneous Voltage-Sensitive Load Reductions
[26] See Chapter 7 for more information regarding load modeling gaps.

- Existing Reliability Standards (e.g. FAC-001) do not require TOs to include in their interconnection requirements any BA- and RC-specific requirements for large loads to address unique local system needs such as operational ramping and oscillation monitoring and mitigation. This is likely a gap.

While FAC-002 requires TPs and PCs to study the reliability impact of large load interconnection and requires that the facilities are studied for "…[a]dherance to applicable…[f]acility interconnection requirements…", there is currently no consideration to ensure that the **as-built configuration and parameters**[27] of these large loads are assessed for conformance with applicable facility interconnection requirements (as created per FAC-001); the review via FAC-001 may only involve the **as-planned configuration and parameters.**[28] Also, without a specific assessment process for design, pre-energization requirements, performance validation, ongoing operation, and future modification, TPs and PCs are not in a position to verify that large loads meet capability and performance requirements prior to energization. This also results in a gap in the ability to assess real-time performance in comparison to assumptions studied and impacts the results of planning studies. FAC-002 requires TOs to coordinate with PCs and TPs on studying the reliability impact of end-user facilities. As large loads are not a NERC registered function, the standard does not mandate any coordination or assistance from the large loads during the interconnection studies.

It is evident that industry lacks well-defined and comprehensive interconnection standards and guidelines for large loads that adequately address the potential risks and reliability concerns that large loads pose to the performance of the BPS. Some regional efforts, such as those undertaken by the Electric Reliability Council of Texas (ERCOT), the Southwest Power Pool (SPP), and other registered entities,[29] are underway to address the reliability impact posed by these large loads, with proposed changes aimed at better integrating these new loads and enhancing the overall reliability of the grid. As noted above, NERC supports federal and state attention to interconnection matters.

Commissioning gaps related to real-time operations and outage coordination are discussed in the **Real-Time Operations and Outage Coordination** sub-section of **Chapter 4**.

Lack of Standardization in Comprehensive Load Interconnection Studies and Performance Requirements

> **Key Point**
> There is a lack of standardization in the interconnection studies and performance requirements for large loads. This can lead to inaccurate forecasting, modeling data, and performance requirements, making accurate analysis challenging.

There is a broad alignment with generation interconnection studies and performance requirements in the industry with many entities following the FERC interconnection procedures and agreements[30] for generators. All TOs are required to have facility interconnection requirements per FAC-001 for both generators and loads. However, for large load interconnections, the process is often affected by local utility tariffs (which are under State jurisdiction), so study approaches and performance expectations vary.

These variations highlight the need for more comprehensive and coordinated study components that ensure accurate modeling data and clearly defined performance requirements. Without such requirements, interconnection studies may yield inaccurate analyses, complicating the assessments of system impacts and the identification of necessary network upgrades. This can affect grid reliability and ability of the system to accommodate the increasing number of large load interconnection requests. Furthermore, the limited input from the BA and RC in the development of the interconnection requirements can create operational risk as TOs and utilities may not clearly understand the specific characteristics and operational requirements of large loads.

[27] The configuration and parameters of a facility following commissioning and tuning, representing its final operational state.
[28] The planned parameters and layout of a facility, based on preliminary engineering design prior to construction or installation.
[29] W-A032522-01 Interim Large Load Interconnection Process
[30] Generator Interconnection

Lack of Data Sharing

The effective interconnection of large loads requires a thorough understanding of the loads' specific operational characteristics, including precise energy consumption profiles, power quality impacts, ramp rates, reactive power needs, and resilience or redundancy measures.[31] However, substantial gaps exist in data transparency and standardization, limiting the ability of grid operators and planners to accurately assess and accommodate these new demands.

One key contributing reason for this gap is that, because most large load customers are not registered entities under NERC standards, there are no direct requirements for the load entities in NERC standards.[32] Furthermore, the entity serving this load may also no longer be a function in the registry criteria. LSEs were a registered function under the NERC registry criteria in the Rules of Procedure (ROP).[33] Based on specific facts and circumstances dating from approximately 10 years ago, the function was removed from the ROP.[34] This white paper examines whether the BPS impacts associated with large loads might warrant reconsidering reactivation of the LSE function to support the efficient integration of large loads into the grid. As most being non-registered entities, data centers and similar large loads are not obligated to comply with stringent data reporting and sharing Reliability Standards typically mandated for generation resources. The lack of clear data reporting and sharing requirements can limit operators' ability to request comprehensive operational and performance data, resulting in an incomplete understanding of these facilities' behaviors and impacts on the grid.

The performance of data centers and other power electronic loads is based in part on their hardware and software configurations, and these configurations can be modified (including after initial energization of the load) resulting in changes to the performance characteristics. As part of the process in FAC-002, PCs should have a definition of qualified change[35] that captures impactful changes to these performance characteristics, as these changes can complicate long-term characterization and modeling of load behavior. However, PCs may not have adequate knowledge of data centers to understand what should be considered a qualified change for data centers or other power electronic loads. This could lead to situations in which a large load performs a configuration change that significantly impacts the performance of the facility but does not meet the PC's definition of qualified change, resulting in these impactful changes not being assessed for BPS impacts via the FAC-002 process.

Data center operators are inherently protective of their operational data due to commercial sensitivity, cyber security concerns, and competitive pressures. Sharing detailed consumption patterns or operational profiles could inadvertently reveal proprietary information regarding internal workloads, operational efficiencies, and business practices. As such, data centers are typically reluctant to provide detailed data, preferring to safeguard their competitive advantage, intellectual property, and sensitive infrastructure details. Operators of cryptocurrency mining facilities in particular may avoid sharing detailed operational data due to market competitiveness and strategic responses to electricity price fluctuations. In addition, utilities do not have observability into different categories of loads that are inside the data centers. This leads to operational challenges amid unexpected load dynamics.

The large load developer can be different than the entity that owns or operates the computational equipment. The developer might not have information on the end-user of the facility until late in the interconnection process. This can lead to gaps in the utility's ability to accurately study the proposed facility earlier in the interconnection process.

[31] See Chapter 7 for more information on the load modeling gaps.
[32] See NERC Rules of Procedure Appendix 5A and NERC Rules of Procedure Appendix 5B for more information on which entities are required to be registered. Available here: Rules of Procedure
[33] Available here: Rules of Procedure
[34] For more information about the history of the NERC Registry Criteria and the removal of certain load-serving entities, see Risk-Based Registration: Phase 1- Enhanced Draft Design Framework and Implementation Plan
[35] See Reliability Standard FAC-002 for more information on the PC defining "qualified change" and the resulting assessments.

This combination of factors creates persistent barriers to robust data sharing and detailed understanding of large loads as well as the modeling of large loads.

Lack of Collaboration and Coordination

The lack of structured communication creates a gap that can result in inefficiencies, misalignment, and increased risk to system reliability. Lack of coordination exists between load owners and the following entities during the interconnection planning, site building, energization, and operation phases of project development:

- Grid operators, owners, and planners
- Regulatory bodies
- State and local governing agencies

Therefore, the coordinated integration of large loads necessitates identification of the stakeholders for every phase of executing the project. Improvement of the collaboration and coordination between these entities will help ensure that large loads can be integrated in a reliable and timely manner.

Moreover, the rapid development timelines of data centers, which can progress from conception to readiness for operation in one to two years,[36] stand in stark contrast to the lengthy timelines required for new transmission and generation infrastructure, which can take four or more years.[37] This mismatch poses significant challenges for ensuring that the grid can accommodate growing demand. To navigate these complexities and support large load integration, deeper collaboration between data center developers and electric utilities is urgently needed.

The LLWG identified a gap in coordination of transmission protection and large load protection. TOs set relay pickups, breaker clearing times, and reclosing schemes on their side of the meter. However, the TOs historically did not need to share those curves with the large load facility owner and operator who program uninterruptible power supply (UPS) and variable frequency drive disturbance ride-through logic. Therefore, the two protection schemes operate independently of one another. Without that visibility and communication, a normally cleared transmission fault can trigger protective systems on the load side even when it is cleared appropriately by the utility. The gap in addressing this risk lies in the current lack of communication and coordination of protective settings from the TO to the large load facility and vice versa. **Chapter 6** further discusses the disturbance ride-through concerns related to large loads.

Certain design considerations (e.g., the facility's transfer to backup power supply and the return to utility during/after voltage disturbances) for large loads can significantly impact the characteristics and risks of that large load as seen by the grid. There may currently be gaps in the coordination between the grid operators/planners and the large load entities regarding these design decisions. This coordination would help ensure that the BPS reliability impacts are considered in the design of the facility. This consideration could also extend to decisions regarding how data center compute is implemented from a software perspective.

[36] The utility may require more time for interconnection.

[37] However, the data centers may not reach their full operational capacity upon initial energization but may ramp up to their full capacity at a later date.

Chapter 3: Planning and Resource Adequacy

Many emerging large loads are seeking to connect to the system in time frames prior to the system planning horizon. This poses planning and resource adequacy challenges, as the amount of load attributed to large loads was not included in long-term planning forecasts, meaning that current transmission planning and generation procurements generally do not account for these new large loads. This can result in the BPS struggling to accommodate the new large loads without resource shortfalls or transmission constraints.

A number of gaps are preventing large loads from being accurately included in new studies. These include a lack of data around emerging large loads (including their demand patterns, project information, and demand responsiveness) and a lack of data standardization and sharing. When information is received by grid planners, it is often only shared when loads are seeking interconnection, which is commonly in the near term and prevents the loads from being included in long-term planning before they are energized. There are also gaps in current resource adequacy studies, practices, and generation procurements as well as transmission planning Reliability Standards.

This chapter identifies the gaps related to planning and resource adequacy. Portions of this chapter related to demand forecasting reflect the research performed by the Energy Systems Integration Group (ESIG) Large Loads Task Force.[38]

Demand Forecasting Gaps

The increase in large loads is impacting system demand in a number of ways. Large loads impact intraday demand shapes as well as seasonal and annual demand patterns. There is also significant uncertainty associated with these loads that makes them difficult to forecast. Traditional load forecasting methods may not be sufficient to capture these changes accurately, for reasons which will be expanded upon below.

Planners lack certainty about key mid- and long-term forecasting parameters for prospective large loads, including the following:[39]

- Schedule for initial energization
- Ramp rate[40]
- Ultimate load after ramping from initial energization
- Load shape (or load factor)

> **Key Point**
> Planners lack a historical basis to assess the collective certainty of some types of large loads.

One reason for this is that planners lack visibility into the certainty of individual large loads' business plans, as some are evaluating interconnection in different areas and most face risks related to construction schedule, technical plans that relate to energization ramps, economic viability, financial challenges, and the comparative cost and schedule for interconnection. Furthermore, planners lack a historical basis to assess the collective certainty of some types of large loads on these forecasting parameters, particularly for novel industrial or data center loads. Accordingly, planners typically apply professional judgment to the available data when evaluating these uncertain forecasting parameters.

Demand forecasts are developed by utilities, system planners, and PCs. The PCs may source some or all of their demand forecasts from member utilities and may also develop portions of the demand forecast themselves. In the

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[38] Large Loads Task Force - ESIG

[39] This list is essentially identical to four of the metrics provided in Figure ES-1 of the ESIG Large Loads Task Force report titled "Forecasting for Large Loads: Current Practices and Recommendations". Available here: Forecasting for Large Loads: Current Practices and Recommendations

[40] Many large loads do not initially energize at their full demand but ramp to this demand over multiple years.

case of information on large loads, PCs, TPs, and RPs are mostly or wholly dependent on information provided by the utilities, which may lead to forecasts relying on what has become out-of-date information.

Key Point
Current resource adequacy practices may not fully account for the complexities introduced by large loads.

Some system planners provide guidance to their members on the information that they require and collaborate with their members on practices. Some utilities and system planners have established standardized practices (e.g., via gates, stages, policy support, financial commitment) for evaluating the key forecasting parameters as large loads request interconnection and engage in obtaining utility service or otherwise securing power. The divergence of large load demand forecasts is a result of the lack of well-established practices, and at least until technology evolution stabilizes, the certainty of those forecasts cannot be guaranteed.

At this time, due to customer confidentiality and the lack of institutional data sharing practices, utilities and regional TPs do not typically share detailed information with one another on the operating characteristics, ramp rates, and load profiles necessary for improved forecasting of the various types of large loads. Development of such practices could compensate for the lack of historical basis for assessing collective certainty of forecasting parameters faced by planners in many areas.

Uncertainty exists around how large loads may participate in peak-shaving, demand-response, or price-responsiveness programs. Program participation has typically been evaluated on a post hoc basis and then factored into resource adequacy and demand forecasts. Existing NERC and regional standards as well as engineering practices do not explicitly address how system operators or planners should incorporate potential large load participation scenarios into resource adequacy and demand forecasts. Without knowing how the loads will participate, utilities are forced to make assumptions that can result in under-procuring both transmission and generation. In a similar vein, there is a gap in requirements for large loads to share information on behind-the-meter generation information at prospective load sites and for utilities on how to include that information when performing studies. Currently, many load forecasters do not obtain adequate information on behind-the-meter generation. This may be because it is not commonly planned. In any case, it is unclear if and how utilities should consider information about behind-the-meter generation in load forecasts and resource adequacy studies. This information is necessary for planners as they consider the impacts of peak-shaving, demand-response, or price-responsiveness programs in their studies.

Resource Planning Gaps

Since NERC Reliability Standards are not directly applicable to most large loads and to LSEs, the information provided to planners from the large load customers or TOs may be inaccurate, challenging long-term planners' efforts to ensure that the system is designed to serve additional load growth and maintain additional generating capacity. Although Reliability Standard BAL-502-RF[41] is applicable strictly to the ReliabilityFirst region, it is indicative of the process that can be used for the determination of an entity's planning reserve margin (PRM). However, large loads are not included explicitly in this standard or mentioned in the context of resource adequacy analysis, representing gaps in this standard. Reliability Standard MOD-031[42] requires registered entities to provide accurate demand forecasts and energy data for resource adequacy planning. However, since neither LSEs nor most large loads are NERC-registered, MOD-031 does not explicitly require information from the owner of the end-user equipment. This can affect the sharing of critical load forecasting data or detailed consumption profiles that represent the consumption of end-user equipment. This omission reduces the accuracy and reliability of resource adequacy studies.

Current resource adequacy studies do not fully account for the impact of new large loads on demand growth and geographic load patterns. The current approach primarily focuses on conventional supply-side metrics and

[41] Available here: BAL-502-RF-03
[42] Available here: MOD-031-3

retirements, which may not be sufficient to address the unconventional yet significant demand posed by these large loads. Furthermore, data centers are bidding into multiple areas for interconnection, which results in overstatement of expected demand for these large loads. Additionally, existing load forecasting methods, procurement strategies, and development of generation and transmission infrastructure may be insufficient to manage the rapid and concentrated growth in demand from large loads.

While resource adequacy planning traditionally focuses on ensuring sufficient generating capacity and reserves to meet expected demand using metrics like loss of load expectation (LOLE) and PRM, existing practices may not fully account for the complexities introduced by large loads. Specifically, the addition of large loads, combined with a number of other factors—such as the increase of variable inverter-based resources (IBR) and distributed energy resources (DER), the frequency of thermal outages during periods of extreme weather (which are becoming more common and less predictable), and aging infrastructure—can all further complicate risk assessment. Additionally, the data used in resource adequacy models to determine PRM does not reflect the effects of large loads in intra-hour behavior and reserve requirements, hourly load shapes, peak and energy forecasts, load forecast uncertainties, and the potential for delays or constraints associated with the development of necessary transmission and generation infrastructure are not considered in resource planning models.

There are no requirements in NERC standards explicitly requiring resource adequacy checks before integrating a new large load onto the system or before the peak demand of an existing large load is increased. This may be a gap in FAC-002. Additional discussion on FAC-002 and related processes can be found in **Chapter 2**.

Transmission Planning Gaps

Large loads are evaluated and planned for by DPs, TOs, TPs, and PCs in various ways depending on their engineering practices, requirements, and the Reliability Standards[43] with which they are required to comply. Transmission planning is based on multiple NERC standards that establish the actions that entities must take to evaluate the BPS and ensure its reliability. Most notably, Reliability Standards TPL-001[44]and MOD-032[45] have been the basis for the development of planning requirements and modeling data submissions for PCs and TPs to perform their work.

TPL-001 establishes planning performance requirements and requires TPs and PCs to conduct annual planning assessments. The event categories in the standard do not explicitly include the loss of large loads unless they are extreme events or unless the load isolated because of the loss of other transmission elements. Another gap in the existing process is in the comprehensive analyses, especially regarding steady-state or dynamic risks due to clustered loss of large loads in an area (e.g., failure to ride through disturbances, sensitive protection settings). As a result, the current evaluations may not be sufficient to plan a system that can accommodate the growing number of large load interconnection requests. Similarly, MOD-032, which establishes the modeling data requirements for the development of transmission planning models, does not adequately cover all modeling requirements for large loads, such as peak demand, load power factor, and dynamic behavior.

The scenario selection for conducting the reliability assessments with large loads is critical in understanding the reliability risks. TPL-001 requires dynamic load models only for near-term studies that look into peak load conditions. However the impacts to the system from the large load could be unique and material during off-peak conditions, when a certain large load[46] might be the biggest load on the system with a very different generation dispatch than was studied in the peak load assessment. These considerations will be important for reliability assessments with large loads. Additionally, TPL-001 does not require load models to be used in long-term stability studies or specify that peak and off-peak conditions should be studied in the long-term stability studies. These may be gaps in this standard.

[43] Historically, the LSE was one of the entities that had standard obligation to provide demand data for these Reliability Standards.
[44] Available here: TPL-001-5
[45] Available here: MOD-032-1
[46] Given that a data center has a very different load consumption pattern as compared to older large industrial facilities like a paper or steel mill.

> **Key Point**
> Traditional planning practices are often focused on the mid- to long-term time frames, while some large loads can connect very quickly in the near-term time frame.

FAC-002 studies help ensure that end-use facilities are reliably integrated to the system. TPL-001 studies focus on the near- to long-term planning horizons spanning 1–10+ years and look at the system from a more holistic perspective. While FAC-002 studies help address many of the impacts from large loads, the TPL-001 studies are still important as they help identify upgrades needed when looking at the overall system. In North America, transmission project development starting from the planning phase to the construction phase can take 5–10 years or even longer to complete. However, it has been observed that some large loads are seeking to interconnect to the system in very short time frames, some within a year. Additionally, some TPs may normally develop models that represent scenarios that are at least two years in future, meaning that such models would not be adequate to assess the impact of large loads interconnecting in shorter time frames. This issue becomes more pronounced for dynamic models as several entities develop dynamic models that represent scenarios at least five years into the future. Therefore, while localized impacts to the BPS from large loads might be addressed in the FAC-002 processes, overall system issues, such as ensuring bulk transfer capability for energy deliverability to clusters of large loads, may not be addressed via TPL-001 processes before the large loads are energized.

Accurately predicting the demand from large loads for long-term planning studies is complex. Misestimations of the magnitude or location of future loads can lead to underbuilding transmission infrastructure or building transmission infrastructure in the wrong locations, which can significantly impact reliability. While many of the issues caused by misestimation of demand can be addressed by FAC-002 interconnection studies for end-use facilities, misestimation of demand can still lead to system-level issues such as lack of bulk transfer capability on the system. It is challenging for TPs or TOs to determine in advance which large load interconnection requests will materialize; however, there is no guidance or Reliability Standards that provide a framework to determine which potential loads to include in long-term planning studies. With the rapid increase in large loads seeking interconnection, load may also outstrip generation in transmission planning cases. TPL-001 does not provide a framework for how to address the situation when load exceeds generation in long-term planning models; there is also a lack of guidance in the industry regarding how to address this situation.

Lack of Standardization/Coordination Between Entities

With current planning practices in some, but not all, markets and areas operating in silos, there can be a lack of standardization and coordination across load forecasting, generation, and transmission planning on how to deal with new large load requests and interest. For example, a regional transmission organization (RTO) may perform transmission planning studies with limited load forecast and generation information provided by LSEs; additionally, there is no standard or guidance for RTOs on how to interpret this load forecast and generation information when conducting studies.

Chapter 4: Balancing and Operations

In the operations horizon, system operators are responsible for ensuring that the BPS is reliable and secure. This includes ensuring that load and generation are balanced, which is required to maintain stability. Many emerging large loads, particularly computational facilities, are power electronics-driven load and are highly responsive (changing consumption patterns based on external triggers) and exhibit pulsating or nonlinear demand profiles and voltage sensitivity to grid conditions. In fact, it is arguable that these large loads can operate as controllable Bulk Electric System (BES)[47] elements that can significantly ramp up and down with high oscillatory behavior, impacting grid reliability. Their size, controllability, and variability introduce potential reliability risks to the BPS comparable to those of a generator but with the added complexity of being on the demand side.

Balancing Gaps

If a BA lacks awareness of large load ramping, the rapid ramping up and/or down of one or more large loads may cause a variety of reliability impacts, including frequency excursions, voltage and thermal violations, and instability risks. The gap in addressing ramping risks affects both real-time operations and the operation planning horizon. This complicates unit commitment decisions and next-day reliability studies. Since there are no specific requirements in place in the NERC standards for large loads to provide necessary information such as large load models and ramp rates to RCs, BAs, and TOPs, the ability to conduct analysis and assessments on the impacts of large load ramping on system reliability is hindered. Without adequate data, real-time operators may not be aware of the risk posed by large loads, and issues may go undetected until they are observed in real time. This could place the burden on real-time system operators to mitigate reliability risks related to voltage violations and frequency deviations in real time.

> **Key Point**
> NERC standards do not provide specific requirements for large loads or LSEs to provide data; this leads to real-time operators being unaware of risks posed to the BPS.

BAs might not have visibility of the demand of individual large loads and may not have sufficient information to know when the large load is expected to increase demand to pre-disturbance levels after a large load demand reduction occurs for a system disturbance. This lack of visibility and information could lead to the BA unnecessarily bringing generation off-line to balance the frequency after a large load demand reduction. If the large load increases its demand to pre-disturbance levels after the BA brings generation off-line, further difficulty in controlling frequency could be experienced. This lack of visibility of individual large load demand (both real-time and forecasted) may be a gap. Additionally, the lack of information may be a gap in coordination between the TOP and BA.

Current gaps in NERC standards also include the absence of explicit requirements to represent or consider the operational behavior of large loads in reliability assessments and situational awareness. While Reliability Standards IRO-010[48] and TOP-003[49] require BAs, TOPs, and RCs to obtain data necessary to perform reliability assessments, these standards do not obligate large loads to provide ramping characteristics, dynamic performance data, or usage profiles. Insufficient data and representation could compromise analysis accuracy, including among new NERC standards like Reliability Standard BAL-007-1 – Near-term Energy Reliability Assessments.[50]

Short-Term Demand Forecasting

Accurate forecasting of large loads in the transmission grid is critical for ensuring BPS reliability. However, several challenges complicate this task, requiring advanced methods and continuous improvements in forecasting techniques. There is a clear gap in how the utilities develop forecasts when considering large loads.

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[47] Glossary of Terms Used in NERC Reliability Standards
[48] Available here: IRO-010-5
[49] Available here: TOP-003-6.1
[50] Available here: BAL-007-1

Load data, especially for large commercial and industrial customers, is often incomplete, aggregated, or lacks necessary granularity, such as hourly or daily usage trends for use in short-term load forecasting. System operators' forecasting methods may not account for rapid changes in load forecasts for industrial and commercial loads caused by business decisions related to the load. Reliability Standards TOP-001[51] and TOP-002[52] cover operations and operations planning. When considering large loads, these standards may not adequately cover the gaps associated with load ramping and forecasts. Additional discussion regarding gaps related to demand forecasting is provided in **Chapter 3**.

Impact of Large load Ramping and Disturbance Ride-Through Limitations on Area Control Error

Large loads can significantly impact a BA's load profile, posing operational challenges in controlling area control error (ACE), the real-time indicator of generation-load balance and interconnection frequency stability. An example of sample ACE variations due to large loads when compared to BA ACE Limits (BAAL) is provided in **Figure 4.1**.

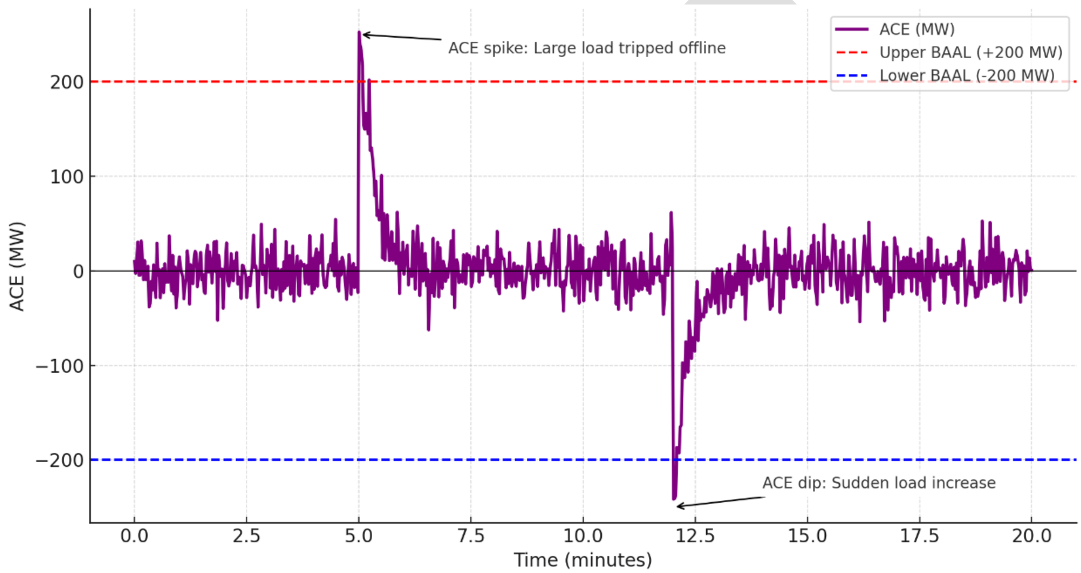

Figure 4.1: Sample ACE Variations Due to Large Loads

- **Existing Reliability Standards contain gaps in addressing the impacts of large loads on ACE:** Although the BAL-001 Reliability Standard[53], which includes Control Performance Standard 1 and Balancing Authority ACE Limit, provides a framework for managing ACE, it does not explicitly account for scenarios where large loads exhibit rapid and unpredictable ramping behavior. This standard requires that "[e]ach [BA] shall operate such that its clock-minute average of Reporting ACE does not exceed its clock-minute Balancing Authority ACE Limit (BAAL) for more than 30 consecutive clock-minutes." Frequency excursions due to large load ramping behavior or other behavior that are corrected within 30 minutes are not a violation of this standard. However, frequency stability may still be at risk in these scenarios. Adherence to the Control Performance Standard 1 requirement in BAL-001 is based on overall performance during the previous 12 months. Sub-optimal performance during one portion of the year can be compensated for with good performance during another portion of the year. As with the BAAL requirement, frequency stability may be at risk in specific timeframes, although Control Performance Standard 1 requirements may be met during the overall 12 months. Additionally, current Reliability Standards lack specific guidance or constraints on how quickly large loads may ramp.

[51] Available here: TOP-001-6
[52] Available here: TOP-002-5
[53] Available here: BAL-001-2

- **Existing NERC Standards do not fully address the need for faster and more flexible balancing actions necessitated by the inherent variability and unpredictability of large loads:** While Reliability Standards BAL-001, BAL-002[54], and BAL-003[55] collectively set standards for overall ACE control and frequency stability, they do not explicitly differentiate the operational treatment between large generator outages and large load perturbations. This lack of specificity could result in inadequate preparedness and insufficient operational tools to manage ACE effectively amid the growing prevalence and unique characteristics of large, dynamic loads.
- **There is a gap in the analysis of the largest reasonable load loss:** All BAs submit their largest credible generator N-1 losses as well as their largest generation loss from a remedial action scheme event as part of the Reliability Standard BAL-003 process. This largest credible loss of generation feeds directly into the calculation that determines the amount of frequency response required from the interconnection and from each BA. If the largest credible load loss is not analyzed on a recurring basis, there could be a gap in preparing for the load loss/reduction events.
- **BAL-002 does not explicitly include large load tripping or ramping events within the balancing contingency event definition:** This standard, focused on the disturbance control standard, primarily addresses the sudden loss of large generation resources or restoration of demand utilized as a resource but does not explicitly include large load tripping or ramping events within the balancing contingency event definition. This represents another critical gap, as the sudden addition or loss of large loads can have equivalent reliability impacts as generation contingencies. Gaps related to large load disturbance ride-through are also discussed in **Chapter 5**.

Additional discussion on gaps related to frequency stability is provided in **Chapter 5**.

Operations Gaps

The following discussions identify gaps related to large load ramping, real-time operations, and outage coordination.

Impact of Large load Ramping on System Reliability and Operations Planning

Today, when operating or planning for operations, system reliability is assessed by evaluating recognized contingency events and monitoring expected outcomes. With respect to large loads, these events could include the loss of a single point of connection for a load station. However, as noted above, multiple large loads in a region could collectively reduce or increase their consumption by unknown amounts, which are not events currently considered in operations or operations planning. These events could lead to reliability issues including thermal violations/exceedances, unacceptable voltage levels and voltage instability, and transient instability of the system.

Currently, planning (TPL-001, FAC-002, FAC-011[56]), operations planning (TOP-002, IRO-008[57]), and operations (TOP-001, IRO-008) related Reliability Standards do not consider the impacts of large-scale ramping, disconnection, and reconnection events. Given the possible significant impacts to the BPS, potentially leading to uncontrolled separation and cascading outages, there is a gap in appropriately considering the impacts of these types of events.

In addition, disturbance ride-through performance remains an area of concern for data centers and cryptocurrency mining facilities that are sensitive to transient voltage drops. These facilities have demonstrated tendencies to disconnect for faults outside of their zone of protection—or more simply for faults on lines they are not connected to—which is unexpected. This type of behavior is not modeled in operational or operations planning analyses, and excessive facility tripping can also lead to thermal violations/exceedances, unacceptable voltage levels and voltage

[54] Available here: BAL-002-3
[55] Available here: BAL-003-2
[56] Available here: FAC-011-4
[57] Available here: IRO-008-3

instability, and transient instability of the system. As discussed in **Chapter 2**, some of the disturbance ride-through performance issues can be due to a lack of communication and coordination of protective settings from the TO to the large load facility and vice versa. Gaps related to large load ride-through are also discussed in **Chapter 5**.

Real-Time Operations and Outage Coordination

Large loads pose a risk to the BPS if their operations are not coordinated with BPS operators. If a large load operates in a way that is not expected by the existing or neighboring RC/TOP/BA, there could be concerns about operating reserves and system stability. To support safe and reliable integration of large loads, TOPs/BAs, RCs, LSEs, and large loads need to coordinate.

As previously mentioned, RCs/BAs/TOPs need data that accurately represents large load facilities to properly account for these facilities in studies and analysis. During commissioning, the system operator needs to conduct multiple checks to ensure the operational readiness prior to energization. RCs/BAs/TOPs may have gaps in the following engineering practices that should be reviewed:

- Pathways for integrating new loads into their modeling tools and energy management systems (EMS)
- Processes for obtaining as-built modeling data and update studies, if required based on changes, prior to initial energization and to integrate the latest data into modeling tools and EMS
- Operational agreements covering communication for normal and emergency operations
- Processes for verifying communication pathways
- Processes for verifying protection configurations and setup including monitoring (such as power quality and oscillation detection)
- Processes for large loads coordinating planned outages with the TO and/or TOP as well as the BA.

Large loads are not currently obligated to establish interpersonal communication capabilities with system operators as outlined in Reliability Standard COM-001.[58] Unlike generators, which must adhere to requirements regarding communication and operating instructions within Reliability Standards PER-005, COM-002,[59] and TOP-001, large loads are not subject to these requirements. These gaps can lead to inefficiencies and miscommunications during critical situations, potentially exacerbating emergencies and hindering effective mitigation efforts.

A key component of maintaining BPS reliability is the ability to coordinate transmission and generation outages to ensure that an outage does not cause a contingency violation or generation shortage prior to the outage. BAs and TOPs currently review transmission and generation outages but not load outages. Reliability Standard IRO-017[60] addresses the outage coordination process for RCs/TOs/BAs but does not consider outages of large loads. The procedures of RCs/TOs/BAs also do not currently cover large load outages.

Operations Tools

Advanced tools like stability analysis or oscillatory signal analysis tools may not be available to operators in real time. These tools are likely needed in areas with high penetrations of IBRs; similarly, they are also likely needed in areas with high penetrations of large loads such as data centers.

[58] Available here: COM-001-3
[59] Available here: COM-002-4
[60] Available here: IRO-017-1

Chapter 5: Disturbance Ride-Through, Stability, and Power Quality

Since large loads can significantly impact BPS reliability, it is crucial to evaluate their performance characteristics, such as ride-through capabilities during grid disturbances, and their effects on system stability and power quality. There are minimal NERC Reliability Standards and regional requirements that adequately capture and mitigate the reliability impacts of large load interconnections to the grid. There are also limited established industry-wide capability and performance expectations (e.g., IEEE 2800[61] for IBRs) for how large loads should be designed and operated to support the needs of the grid or avoid negatively impacting BPS or local reliability. IEEE and International Electrotechnical Commission (IEC) standards applicable to large loads regarding harmonics and other factors exist, but there are no requirements to help ensure that large loads do not negatively impact BPS reliability. For more information on simulation tools, modeling terminology, and application of the tools and models, see **Appendix A**.

Voltage Disturbance Ride-Through Gaps

Many large loads have internal protection and control systems that are sensitive to grid disturbances. As a result, large loads are prone to disconnect or transfer load to backup systems during normally cleared system faults. Large load ride-through capability and performance need to be studied and understood by system operators. Otherwise, this lack of disturbance ride-through can lead to large amounts of load disconnecting or reducing demand during voltage and frequency perturbations that would not normally result in such behavior. This limited voltage disturbance ride-through capability can pose multiple reliability challenges to the grid, such as balancing and stability impacts. The protection and control standards such as Reliability Standards PRC-019,[62] PRC-024,[63] and PRC-029[64] do not discuss large load performance during voltage and frequency deviations.

NERC Reliability Standards and regional requirements that dictate how system studies and analyses are performed do not conventionally assess transmission contingencies that involve the simultaneous loss of nearby voltage-sensitive load in addition to one or more faulted transmission facilities. Without predictable disturbance ride-through performance from large loads, such as the performance required by generators with the enforceable Reliability Standard PRC-029 or even the voluntary IEEE 2800, conducting studies to appropriately gauge and mitigate this risk is challenging. Additionally, there is a gap in capturing high-resolution data needed for studies and analyses that assess the performance characteristics of large loads. NERC standards like Reliability Standard PRC-028[65] lack data monitoring requirements for large loads to assist TPs and PCs with disturbance ride-through performance evaluations.

There is a lack of coordination and data sharing between RCs, BAs, TOPs, TOs, TPs, and large load entities on how and when large loads should ramp to pre-disturbance demand levels upon voltage recovery after a voltage disturbance. Because of this, the BAs in the system may reduce total generation due to an observed high frequency after a large load demand reduction or trip event, not knowing when the load will return to pre-disturbance demand levels. However, after the generation has been re-dispatched, large loads might suddenly begin ramping back to the grid, causing frequency to drop due to the mismatch of generation levels and load levels. Additionally, this return to pre-disturbance demand levels after a voltage disturbance cannot be studied in simulation due to lack of information being shared regarding when and how quickly the load will return to pre-disturbance levels; this presents a significant gap between system response in simulation studies compared to what may happen during a real event. In

[61] Available here: IEEE 2800-2022
[62] Available here: PRC-019-2
[63] Available here: PRC-024-3
[64] Available here: PRC-029-1
[65] Available here: PRC-028-1

comparison, ride-through performance and recovery of IBRs during system disturbances have been well defined and adopted in performance standards such as PRC-029.

RCs, BAs, and TOPs may use the Information Technology Industry Council (ITIC) curve to make assumptions about when large electronic loads will reduce consumption or transfer to backup UPS or generation. The ITIC curve is commonly used in the design of IT equipment, such as computers and servers. The ITIC curve is applicable to power supplies, but it may not be applicable for grid studies if there is a UPS between the grid and the power supplies. UPS settings or other site-level protections may impact the disturbance ride-through characteristics of the load. Disturbance ride-through characteristics may vary significantly between large load facilities, which may notably impact area-wide studies involving loss of large loads during grid disturbances. This is another potential gap due to the lack of verifiable large load ride-through data as previously mentioned.

IEEE Standard 1668[66] provides recommended practices for voltage sag and short interruption ride-through testing for end-use electrical equipment rated below 1,000 V. The Tennessee Valley Authority uses this standard to assess the voltage sag ride-through performance of large loads, including industrial and data center loads. Compatibility with IEEE 1668 allows loads to ride through the most common transmission-caused voltage sags but allows load to trip off-line for deeper or longer voltage sags. Although this standard does provide recommended disturbance ride-through capability of end-use equipment, it does not establish minimum ride-through performance requirements for large loads connecting to the BPS.

The absence of a clearly defined voltage disturbance ride-through capability leads to highly variable responses among large loads. Furthermore, RCs, BAs, and TOPs often lack visibility into these behaviors. Large load interconnection requests do not currently require submission of dynamic models with specified disturbance ride-through capabilities, nor are such capabilities typically verified through testing after commissioning.

Key Point

The absence of a clearly defined voltage ride-through capability leads to highly variable responses among large loads.

However, entities including ERCOT, SPP, and Dominion Energy are developing disturbance ride-through requirements for large loads. This work will help to address the gaps discussed above.

Frequency Disturbance Ride-Through Gaps

Frequency disturbance ride-through refers to the ability of a resource to remain connected to the grid during system frequency deviations within defined thresholds and durations. This capability supports grid stability by preventing unnecessary tripping of generation resources during events so the system can recover.

Frequency disturbance ride-through standards are currently focused on generators, with no equivalent requirements established for large loads. While loads are generally expected to remain connected through “reasonable” frequency disturbances, there is no formal definition of what constitutes reasonable, nor any enforceable criteria for performance. Historically, loads dropping off during low-frequency events has been a net positive for grid reliability. However, if large loads trip or transfer to backup generation for high-frequency events, the problem could be exacerbated. This identifies a potential gap since large loads fall outside the scope of existing NERC Reliability Standards that govern frequency disturbance ride-through.

PRC-024 and PRC-029 define the allowable frequency and voltage protection settings for generating resources, ensuring that generators do not trip off-line during system disturbances that fall within a defined “no-trip zone.” The intent is to ensure that generator protection settings do not exacerbate grid instability. Although PRC-024 and PRC-029 were written for generating resources, some elements of the standards may have relevance when considering

[66] Available here: IEEE 1668-2017

performance expectations for large loads, particularly the sections that define frequency thresholds and minimum ride-through times.

Similarly, IEEE 2800 sets performance requirements for IBRs, including frequency disturbance ride-through capabilities. IEEE 2800 applies to generation resources only and does not address load facilities. PRC-024 and PRC-029 are also only applicable to generation resources. However, it is worth noting that both these NERC standards and the IEEE standard provide a structured framework for how resources interact with frequency disturbances on the grid, which could potentially inform future approaches to load behavior.

Harmonics and Interharmonics Gaps

Electronic devices such as adjustable speed drives, rectifiers, and switched-mode power supplies—commonly found in emerging large loads—produce harmonics and interharmonics[67] that can contribute to unacceptable levels of voltage and current distortion in the BPS. While the large quantity of electronic devices present in emerging large loads is remarkable, existing standards provide guidance on acceptable limits that can be effectively applied to large loads.

IEEE Standard 519 establishes voltage and current distortion limits that, if followed, minimize the chances of adverse impacts related to distortion. As the limits set by IEEE 519[68] are intended to ensure compatibility between the load and public power supply system, they are applied exclusively to the point of common coupling (PCC) and do not apply to individual devices or buses within the facility. In IEEE 519, management of distortion is seen as a joint responsibility between the system owners or operators and the user (e.g., the owner/operator of the large load). Broadly speaking, the user is responsible for limiting the current distortion that their loads produce, whereas the grid operator is responsible for limiting the voltage distortion that is produced when distorted currents flow through system impedances. The guidelines defined in IEEE 519 can be effectively applied to large loads. The standard specifies allowable distortion limits for nominal voltages ranging from 120 V to above 161 kV. The standard accounts for the fact that larger loads can have greater effects on voltage and current distortion. Allowable limits are adjusted based on the short-circuit ratio of the user's facility and nominal voltage of service. Users connected to higher voltages and lower short-circuit ratios have the potential to produce greater distortion and are therefore subjected to stricter limits.

Some large load sites have significant quantities of generation (more than or equal to 10% of the annual average load demand). If this generation contains IBRs and/or DER, IEEE 519 may not be applicable—either IEEE 2800 or IEEE 1547[69] should instead be referred to for harmonic and interharmonic limits. IEEE 2800 addresses transmission-connected IBRs and IEEE 1547 addresses DERs.

IEEE standards provide requirements that can be applied to limit harmonics; the limits, applicable to both voltage and current, are common to all large load interconnections without any further coordination among them. However, lack of coordination among different large load interconnections may create situations where individual loads are compliant with limits at their connection point but create non-compliance at other portions of the system (in comparison, other jurisdictions, such as most European transmission system operators, provide individual harmonic emission limits to each customer and these are enforced as part of the compliance process).

Some industry practices may have gaps when it comes to determining interharmonic limits. IEEE 519 does not provide universally applicable limits for interharmonics. This is because the sensitivity of differing loads to interharmonics varies significantly, and a set of limits intended to accommodate all possibilities appeared to be very restrictive to the

[67] The term "interharmonic" is used as defined in IEEE 519-2022 and encompasses subharmonics and supraharmonics as well.
[68] Available here: IEEE 519-2022
[69] Available here: IEEE 1547-2018

committee that developed IEEE 519. Thus, if a large load is anticipated to produce interharmonics, analyses beyond those defined in IEEE 519 are likely necessary.

Some system owners/operators may encounter instances where there are no existing technical solutions by which a large load can meet typical interharmonic limits. While the technical solutions themselves are not the focus of this white paper, the possibility that it may not be technically feasible to employ standard limits does indicate an important gap in industry practices. Prior work by the IEEE Interharmonic Task Force suggests that interharmonic voltages in the subharmonic range[70] should be limited to less than 0.1% of nominal.[71] Some AI workloads may produce subharmonics that are tens or hundreds of megawatts in magnitude. Reducing subharmonic magnitudes below suggested limits is sometimes beyond the capability of traditional solutions such as static VAR compensators. Load smoothing with utility-scale battery storage and grid-forming inverters can reduce the subharmonic current magnitude by roughly 70%.[72] Other methods for load smoothing include static synchronous compensators[73] with supercapacitors.

Some industry practices may have gaps when it comes to managing transmission system voltage distortion. Even if the anticipated current distortion produced by the large load is within the current limits recommended in IEEE 519, high system impedance or an electrical resonance (e.g., involving a nearby transmission system capacitor) may still result in unacceptably high voltage distortion. System owners/operators who have previously had very little current distortion present in their transmission system may not have practices in place to proactively identify and mitigate unacceptable levels of transmission voltage distortion.

Stability Gaps

Maintaining a stable power system requires addressing a broad range of issues. For consistency and clarity, gaps related to stability problems are discussed in terms of the taxonomy shown in **Figure 5.1**.[74] Forced oscillations are also discussed in this section. Even if the power system is technically stable, forced oscillations can interact with the dynamics associated with different stability problems in a way that can cause power outages or equipment damage.

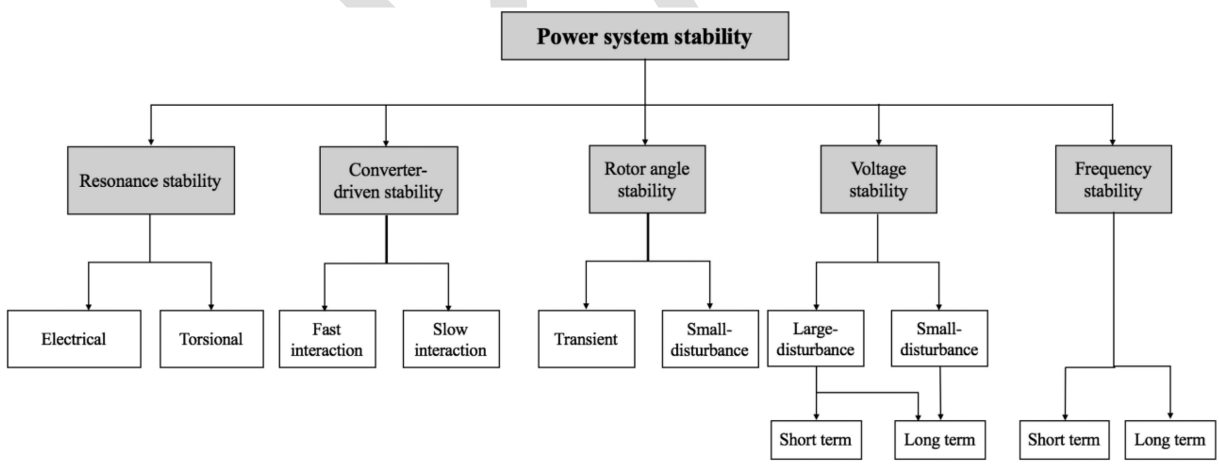

Figure 5.1: Taxonomy of Power System Stability

[70] Interharmonics with frequencies that are "below the system fundamental frequency" (IEEE 519-2022)
[71] See Issues and Challenges Related to Interharmonic Distortion Limits
[72] See page 77 of LLTF April Meeting & Technical Workshop Presentations
[73] Also known as STATCOMs
[74] See Definition and Classification of Power System Stability -- Revisited and Extended

- Gaps relating to rotor angle stability, voltage stability, and frequency stability primarily relate to concerns that the existing practices used to conduct transient stability studies are not accurate or comprehensive enough. These concerns stem from ways in which emerging large load dynamics differ from most traditional load.
- Gaps relating to resonance stability and converter-driven stability are more fundamental in nature; the specific mechanisms by which large loads might contribute adversely to converter-driven or resonance stability are ill-defined, representing a major obstacle to defining study and modeling requirements clearly enough for practices to be developed around them.

Because accurate modeling is an essential part of maintaining power system stability, many of the gaps relating to stability are modeling related. General gaps in large load modeling practices are discussed in **Chapter 7**, and the scope of modeling discussions in the following subsections is limited to specific modeling gaps that are important for the stability studies under discussion. All models are flawed, and different stability problems require different modeling approaches. Each kind of stability study will require practice improvements tailored to the study's specific purpose.

Rotor-Angle Stability

Large loads can produce rapid and significant fluctuations in real power that can result in generators swinging beyond their rotor-angle stability limits and losing synchronism. There are gaps in the models used and scenarios considered in the transient stability studies used to identify specific contingencies where rotor-angle stability might occur.

- **Model-related gaps stem primarily from the lack of well-defined disturbance ride-through behavior, as discussed earlier in the chapter:** Existing load models used to represent large loads in transient stability studies do not accurately predict whether the large loads will trip off-line or remain connected during a given disturbance.[75] They also may not accurately predict large loads' real and reactive power consumption during the fault or postfault recovery and/or reconnection dynamics. All these modeling aspects can significantly affect the outcome of rotor-angle stability studies. Note that, from a stability and modeling perspective, the essential gap is not necessarily the lack of formal requirements, it is the mismatch between the models and reality.
- **Contingency-related gaps are likely present because large loads can produce system-level impacts in scenarios that differ from those typically included in transient stability studies:** For example, a control misconfiguration or settings error at a large load site could theoretically result in a gigawatt-scale load coming on-line in only a few power system cycles. Thus, it may be necessary to expand the contingencies considered in studies such as those done to meet TPL-001. What these additional contingencies should be is unclear.

Frequency Stability and Voltage Stability

The model- and contingency-related gaps for frequency stability studies and voltage stability studies are similar to those discussed for rotor-angle stability. The primary gaps for frequency stability studies are that the large load modeling practices are insufficiently accurate and commonly considered scenarios may not be sufficiently conservative. These gaps apply both to issues related to frequency stability and managing rate of change of frequency. For voltage stability studies, the dynamic performance of large loads during voltage deviations is the primary area needing better fidelity.

Key Point

The primary gaps for frequency stability studies are that the large load modeling practices are insufficiently accurate and commonly considered scenarios may not be sufficiently conservative.

[75] It is worth noting that the ride-through characteristics of large loads can depend in part on whether the load has a leading or lagging power factor.

Automatic under-frequency load shedding (UFLS) programs are essential for maintaining frequency stability. The disconnection of a large load in a UFLS scenario could exacerbate ongoing reliability issues. For this reason, large loads are inherently difficult to integrate into UFLS programs. Studies need to be performed to evaluate whether the disconnection of that large load could cause further reliability concerns. These studies may need to be performed at interconnection, not just on the five-year Reliability Standard PRC-006[76] UFLS study cycle. Additionally, the five-year PRC-006 UFLS study frequency might not be often enough, because the rapid growth of large loads might significantly change the results of these studies in some areas, even if the large load is not part of the UFLS program.

PRC-006 defines design and documentation requirements for automatic UFLS programs. It intentionally avoids prescribing the method by which utilities meet these requirements. The practices that utilities employ to meet PRC-006 requirements will likely need to be revised. There may also be gaps relating to how automatic UFLS settings are coordinated with any frequency disturbance ride-through requirements to which the large load is subjected via its interconnection agreement.

UFLS entities (the entities that provide automatic load tripping), such as TOs, are required to have available a load-shed amount above a minimum per their PC's UFLS program to ensure that enough load can be shed to arrest frequency decline and avoid complete grid collapse in case of severe low-frequency events. Large loads might not currently be included in UFLS programs. Thus, an interconnecting large load introduces a potential reliability risk that the UFLS entity's existing load-shed amount may fall below the minimum load-shed amount and hence may fail to arrest frequency decline if a severe low-frequency event occurs. The fact that the large load may not be added to the UFLS program may be a gap in utility practices.

Additionally, the manual or UFLS shedding of the entirety of a very large load could lead to over-frequency or overvoltage. The ability to partially shed large loads, either manually or as part of a UFLS scheme, may not be part of existing utility practices.

Undervoltage load shedding (UVLS) programs are an essential tool for mitigating voltage stability problems. The inclusion of large loads in UVLS schemes introduces challenges similar to those associated with their inclusion in UFLS programs. Reliability Standard PRC-010[77] establishes an integrated and coordinated approach to the design, evaluation, and reliable operation of UVLS programs. There may not be any gaps in PRC-010, but there are likely gaps in the ability of existing UVLS design strategies to reliably include large loads.

There may be gaps related to the coordination of UVLS programs and voltage disturbance ride-through requirements placed on large loads. Requiring large loads to remain connected during disturbances such as faults may mitigate rotor-angle or frequency stability problems by better maintaining generation-load balance following system disturbances. However, a large load maintaining full consumption during undervoltage conditions will increase the dynamic reactive power support necessary to maintain voltage stability. Thus, the effects of changes in disturbance ride-through requirements must be considered in UVLS program design. As disturbance ride-through requirements for large loads are being developed in many parts of North America, the coordination of UVLS programs and voltage disturbance ride-through requirements should be considered.

Interconnection Frequency Response

The first portion of the stated purpose of BAL-003-2 is "[t]o require sufficient Frequency Response from the Balancing Authority (BA) to maintain Interconnection Frequency within predefined bounds by arresting frequency deviations and supporting frequency until the frequency is restored to its scheduled value."[78]

[76] Available here: PRC-006-5
[77] Available here: PRC-010-2
[78] BAL-003-2

Current calculations for required frequency response (Interconnection frequency response obligation, measured in MW per 0.1 Hz) are based on the margin to the first level of UFLS in each Interconnection but do not separately consider the margin to system over-frequency limits. This is especially important because the considerations and equipment tolerances for over-frequency conditions may be different from that of under-frequency conditions. The assumption that these considerations and equipment tolerances are exactly the same has previously been adequate due to load losses historically being much smaller and less frequent compared to generator losses.

Additionally, large load facilities do not always have good dynamic models showing trip and reduction behaviors and do not always provide the models to all appropriate entities that need them in order to assess potential risks to frequency stability from customer-initiated load reduction events. BAs will need accurate dynamic models in order to reliably assess these risks; therefore, the fact that current models have limited ability to reflect the load reductions is a gap and the fact that accurate dynamic models are not required for all BAs is a gap. The gaps related to load modeling are further discussed in **Chapter 7**.

Additional discussion regarding frequency stability and balancing gaps is provided in **Chapter 4**.

Converter-Driven Stability

Existing practices are unable to adequately define the essential issues underlying converter-driven stability.[79] In order to identify and study a specific converter-driven stability problem, especially at the planning stage (where very little is known about the power converters that will be used by the large load), it is generally necessary to have both a well-bounded idea of the kind of issue at hand and a high-fidelity model that has been designed to replicate the issue. There is currently no clear understanding of the specific kinds of converter-driven stability issues to which large loads will be prone. Without this, study practices and model requirements cannot be effectively defined. Even the most detailed electromagnetic transient (EMT) models must omit some potentially relevant control details.

While this white paper later details gaps relating to high-fidelity modeling (see **Chapter 7**), gaps relating to converter-driven stability should not be viewed as solely, or even primarily, a modeling gap, nor should it be assumed that addressing gaps related to modeling will address gaps relating to converter-driven stability. Many control interactions involving power converters are not identified proactively using studies but rather observed in the field unexpectedly.[80] Often, the control interactions are, by their very nature, the result of inevitable differences between models and reality. These differences may come from minor variations in model implementation, settings errors or device malfunctions, or changes in system or site conditions that take place after the study is performed.

For system owners/operators who have experience with converter-based stability problems, existing practices for managing converter-driven stability primarily consist of identifying system-level factors that have historically proven influential in converter-driven stability issues. The presence of flexible ac transmission system devices, HVdc lines, and IBRs has been a common factor in historical issues with converter-based stability. Weak grid conditions often contribute to the issues. If the presence of these system-level factors is identified, more detailed studies are performed. The proximity of large loads to other large-scale power electronics devices can provide some use baseline for identifying cases of concern, but this criteria is far from the level of detail needed for productive study of the converter-driven stability of large loads.

Converter-driven stability issues are not common and require specialized expertise to analyze. Many system owners/operators may have gaps in their existing practices due to a lack of prior need to analyze such issues.

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[79] See the Stability section of Chapter 3 of the White Paper: Characteristics and Risks of Emerging Large Loads for more information on convertor-driven stability.

[80] See Data Center Power System Stability — Part I: Power Supply Impedance Modeling,
ERCOT experience with Sub-synchronous Control Interaction and proposed remediation,
Large Load Oscillation Event, and
Understanding the Inception of 14.7 Hz Oscillations Emerging from a Data Center

There may be gaps in Reliability Standards such as TPL-001, FAC-001, FAC-002 and MOD-032 relating to study requirements for converter-based stability issues involving large loads. However, until the issues themselves are better characterized, gaps in Reliability Standards defining practices for modeling and studies will be difficult to assess accurately.

Resonance Stability

Many of the gaps discussed in the section on converter-driven stability apply to resonance stability as well. The essential nuance is that resonance stability issues can involve other devices, such as series or shunt capacitors and turbines. The practice currently employed by some system owners/operators is to identify the proximity of the large load to such devices and then initiate detailed EMT studies. However, this is subject to the same drawbacks and limitations associated with current approaches for studying converter-driven stability in large loads.

Forced Oscillations

Large loads can be a source of significant forced oscillations in the 0.1 Hz to 30 Hz range, either as the result of unintended control interactions or as part of their processes (e.g., AI training). There are significant gaps when it comes to defining allowable limits for forced oscillations in terms of BPS reliability. These forced oscillations can excite oscillatory dynamics in the power system, such as electrical resonances, interarea modes, and torsional modes, potentially leading to far-reaching impacts to BPS reliability. However, there are no guidelines or limits by which a system owner/operator can identify that a given forced oscillation is a reliability risk.

> **Key Point**
> There are significant gaps regarding the defining of allowable limits for forced oscillations.

IEEE 519 guidance surrounding interharmonics is of very limited applicability; the limits given therein are very stringent, and violations are sufficient only to indicate that nearby users with sensitive loads may experience issues. Power quality violations are not sufficient to indicate an imminent reliability risk, and power quality standards are not intended to be used as a basis for meeting reliability requirements.

Some system owners/operators do conduct screening studies to evaluate whether forced oscillations from proposed large loads might interact with oscillatory modes in the power system, but these are not required by any Reliability Standards, nor are there guidelines regarding what level of interaction is acceptable.

Some system owners/operators do perform oscillation detection and localization in an operational setting and use this to identify oscillating loads. However, adoption of such tools varies widely throughout industry. Again, the lack of acceptable limits for system reliability remains a challenging gap. Even if an oscillating load is identified, there is no established practice for determining whether the oscillation is a risk to reliability and what level of urgency is associated with the issue.

Chapter 6: Security, Resilience, and Event Analysis

While data centers and other emerging large loads have security practices, existing practices, requirements, and NERC Reliability Standards may present security gaps concerning large loads, particularly with the increasing complexity of large loads and their integration of advanced technologies. Reliability Standards are not directly applicable to most large loads as most of them are not NERC registered entities; therefore, the Reliability Standards do not directly provide a minimum level of security measures to be implemented by the large loads. While Critical Infrastructure Protection (CIP) Reliability Standards provide a framework for cyber security, their applicability and granularity concerning the unique operational characteristics and potential vulnerabilities of emerging large loads, such as data centers and industrial facilities with behind-the-meter power generation/microgrids/demand-side management capabilities, may not be fully comprehensive. The growing adoption of internet-connected control systems and the potential for these loads to utilize these control systems introduces new cyber-attack vectors that might not be adequately addressed via current standards or industry protocols. Furthermore, the physical security of these large load sites and their potential impact on grid stability during both normal operations and cyber incidents may require a more holistic and adaptive security approach that goes beyond traditional utility- or ISO/RTO-centric perspectives.

The LLWG has not identified any system restoration gaps related to large loads because large loads will not usually be included in restoration plans. However, if large loads are included in restoration plans, then there are considerations needed to ensure that the load does not impact the stability of the island.

The lack of large load registration can also potentially impact event analysis by making it more difficult to acquire information on an incident. This leads to difficulty in identifying and implementing corrective actions and developing lessons learned for industry. Additionally, there are no Reliability Standards requiring disturbance monitoring equipment. This is a potential gap as high-resolution data provided by disturbance monitoring equipment is essential to monitoring and analyzing the performance of large loads during events such as voltage disturbances and oscillations.

Physical and Cyber Security Gaps

Physical security threats to large loads are diverse, ranging from theft and vandalism to sabotage and insider threats. Environmental factors like severe weather also pose risks. Vulnerabilities often arise from the size and complexity of these loads, extensive perimeters, reliance on cyber-physical systems, aging infrastructure, and human factors. A security gap for some large load categories may be a lack of design basis threat assessments. These assessments define potential adversaries' capabilities and intentions, serving as a benchmark for designing and evaluating security systems. Regular design basis threat reviews are essential to adapt to evolving threats.

NERC Reliability Standards, including CIP-006,[81] CIP-008,[82] and CIP-014,[83] aim to enhance the security and resilience of the BPS. These standards are not directly applicable to large loads since most large loads are not registered entities under NERC's purview. While these standards are also not applicable to generators, the lack of applicability of these standards to large loads may be a gap.

- CIP-006 focuses on the physical security of BES cyber systems, mandating measures like access control, surveillance, and alarm systems to protect against compromise.
- CIP-008 focuses on cyber security incident reporting and response planning.

[81] Available here: CIP-006-6
[82] Available here: CIP-008-6
[83] Available here: CIP-014-3

- CIP-014 specifically addresses physical security for critical transmission equipment and substations, requiring risk assessments and security plans to protect against physical attacks. The benefits of CIP-014 include ensuring grid reliability, reducing risks from physical threats, and building trust in the security of critical infrastructure.

While CIP-014 is a significant security Reliability Standard, areas for improvement or potential gaps may include the depth of risk assessments required and the need for more specific minimum physical protection standards across a broader range of BES assets. This may be a gap related to the CIP Reliability Standards.

Cyber security gaps concerning NERC BPS threats and vulnerabilities might pose significant challenges to the reliability of the electric grid, especially as emerging technologies introduce new risks. Adversaries could exploit vulnerabilities in systems governed by standards issued by standards organizations like the IEEE, the IEC, the National Institute of Standards and Technology (NIST), the International Organization for Standardization (ISO), and NERC. These standards help to safeguard the BPS, but changes to these standards may be needed due to the evolving threat landscape. One critical gap might be in the monitoring and control of interconnected systems such as data centers or energy Internet of Things (IoT) devices employed by large industrial loads (with and without sophisticated microgrids and/or behind-the-meter power generation capabilities). Adversaries could coordinate cyber attacks that might intentionally overload the grid or initiate simultaneous disconnections that might destabilize the system. Similarly, vulnerabilities in IoT devices with BPS applications often lack robust security protocols. This could present a backdoor for cyber attacks that could allow adversaries to impact the BPS.

Data centers also present unique risks due to their massive and variable power demands. [84] Attackers may be able to manipulate workloads, potentially changing the demand of the load. These manipulations fall outside traditional operational parameters and may highlight the gaps in current cyber security frameworks; data center security protocols are not reviewed or vetted via NERC standards.

Communication Security Gaps

Security gaps related to information sharing and data communication protocols for large loads present significant challenges.

- **A primary concern lies in the diverse and often proprietary nature of communication protocols used by different components and systems within a large load infrastructure.** This heterogeneity can create silos of information, which can hinder effective and timely sharing of critical security data, such as sensor readings, access logs, and threat intelligence. Inconsistent data formats and a lack of standardized communication protocols can impede interoperability between security devices and control systems, making it difficult to achieve a holistic view of the security posture.
- **The reliance on legacy communication protocols, which may lack robust encryption and authentication mechanisms, exposes sensitive operational and security data to potential interception and manipulation.** Insufficiently secured communication channels between remote monitoring stations and the large load site may also be a vulnerability, as unauthorized access to these channels could allow attackers to gain insights into operations or even issue malicious commands.
- **The absence of well-defined and enforced data sharing policies, including protocols for incident reporting and information dissemination among relevant stakeholders, could further exacerbate security gaps by delaying response times and hindering coordinated mitigation efforts.**

[84] See White Paper: Characteristics and Risks of Emerging Large Loads for more information on the risks posed by data centers to the BPS:

- **The increasing integration of IoT devices and cloud-based services into large load management introduces new attack vectors and complexities in securing data communication pathways and ensuring data integrity across distributed environments.**

Operational Security Gaps

Key Point

No NERC standards provide requirements to prevent bad actors from accessing and controlling operational systems related to large loads.

While large loads have security measures implemented, no Reliability Standards provide requirements to prevent bad actors from accessing and controlling operational systems related to large loads and their inherent energy demand profiles. Bad-actor control of a large load could result in excessive ramp rate, oscillations, or other performance aberrations that could impact the BPS. Furthermore, no Reliability Standards provide requirements to prevent an insider threat from accessing operational systems of large loads. Reliability Standard PER-003[85] requires RC, TOP, and BA staff performing reliability-related tasks associated with the respective entity's functions to have NERC certifications. These certifications ensure that staff members are competent in the necessary areas. However, no such standards exist applicable to large loads. Additionally, PER-005 provides requirements for the training of system operators and specific GOP dispatch staff; Reliability Standard PER-006[86] also provides requirements for the training of GOP personnel. Again, no such standards are applicable to large loads.

While multiple Reliability Standards touch upon personnel security and training, the CIP Reliability Standards are the most directly relevant to mandating employee vetting. Reliability Standard CIP-004[87] focuses on minimizing the risk of compromise to BES cyber systems by individuals with authorized access. CIP-004 mandates a baseline level of employee vetting through identity verification and criminal background checks for individuals who have access to critical cyber assets within the North American BPS. This is a crucial component of a layered security approach aimed at mitigating insider threats and ensuring the reliability of the grid. It is important to note that, while CIP-004 is the most direct Reliability Standard addressing employee vetting, other CIP Standards related to physical security (e.g., CIP-006) and access control (e.g., Reliability Standard CIP-007[88]) also have implications for who is granted access to critical facilities and systems, thus indirectly relating to personnel considerations. Lastly, as previously stated, PER-005 focuses on the qualifications and training of personnel but does not specifically mandate the initial vetting process in the same way as CIP-004. Again, these CIP and Personnel Performance, Training, and Qualifications (PER) Reliability Standards are not applicable to large loads.

The lack of requirements for limiting access and control of large loads and for the training of operators of large loads may be a gap in the NERC Reliability Standards.

Existing NERC registered entities rely upon event reporting frameworks within the EOP-004[89] and CIP-008 Reliability Standards to communicate material cyber and physical security event details to regulators and other electric market participants. Large load asset owners have no such mandate related to event reporting for the purpose of grid integrity, reliability, and resilience. This may be an operational security gap.

[85] Available here: PER-003-2
[86] Available here: PER-006-1
[87] Available here: CIP-004-7
[88] Available here: CIP-007-6
[89] Available here: EOP-004-4

System Restoration

The LLWG does not see any gaps regarding large loads in practices, requirements, or Reliability Standards related to system restoration as large loads will not usually be included in restoration plans.

Key Point

Because large loads will not usually be included in system restoration plans, the LLWG has not identified any gaps related to large loads and system restoration.

- The initial loads energized during system restoration are chosen primarily for the purpose of controlling frequency and voltage. Because of the size of large loads and because of the disturbance ride-through characteristics and varying demand of large loads, large loads will likely not be energized in the initial stages of system restoration due to the risk to the stability of the island.
- The choice of loads to restore may be prioritized by criticality, such as loads serving hospitals. Large loads may serve a critical function, but these will likely have backup generation and the need for prioritized restoration would be evaluated on a case-by-case basis.

However, if a large load was included in a system restoration plan, then aspects such as varying demand, disturbance ride-through, and other characteristics of the load need to be studied to ensure that the load does not impact the stability of the island.

Event Analysis and Data Collection Gaps

NERC, the Regional Entities, RCs, GOs, and TOPs typically have standard practices for grid event analysis that require coordination and communication between multiple entities. If additional information is needed for a particular event, NERC, the Regional Entities, and RCs have the ability to send requests for information to authorized representatives of the applicable entities to initiate root-cause analysis and develop mitigation plans when necessary. Registered entities are required to respond to requests for information according to Section 1600 of the NERC ROP.[90] If the analysis of the event uncovers potential violations of existing Reliability Standards, regional requirements, or utility best practices, the applicable entity can be required to develop and implement a corrective action plan to mitigate the potential of similar future events.

Lack of LSE and large load registration can impair event analysis of incidents involving large loads. Multiple events in the Eastern Interconnection (EI)[91] and ERCOT[92] have involved large loads reducing significant amounts of load during voltage disturbances; data center oscillations have also been observed.[93, 94] The significant gaps in existing practices, requirements, and standards can impair NERC and the Regional Entities from obtaining the needed information directly from the large load entities to perform thorough root-cause analysis on these events. Therefore, it is difficult to identify and implement proper corrective actions and develop lessons learned to prevent additional events.

There are existing Reliability Standards and regional requirements for GOs and TOs regarding disturbance monitoring and reporting requirements. Examples include Reliability Standards PRC-002[95] and PRC-028 and ERCOT Nodal Operating Guide[96] Section 6.1. These standards and requirements mandate the installation and configuration of disturbance monitoring equipment (DME) such as digital fault recorders, dynamic disturbance recorders, and phasor measurement units. Standards include location requirements and requirements to provide data to requesting entities such as NERC, the Regional Entities, and RCs within specified timelines. ERCOT revised Nodal Operating Guide Section

[90] Available here: Rules of Procedure

[91] See Incident Review - Considering Simultaneous Voltage-Sensitive Load Reductions

[92] See *ERCOT Large Load Loss/Reduction Events 2020-2024* presentation from the December 12, 2024, NERC LLTF meeting. December 2024 LLTF meeting presentations available here: https://www.nerc.com/comm/RSTC/LLTF/LLTF_Presentations_December_12_2024.pdf

[93] See Understanding the Inception of 14.7 Hz Oscillations Emerging from a Data Center

[94] See Data Center Power System Stability — Part I: Power Supply Impedance Modeling

[95] Available here: PRC-002-5

[96] Available here: Current Nodal Operating Guides

6.1 in 2024 to state that the interconnecting TOP of a large load with peak demand greater than or equal to 75 MW must install and configure DME upon request from ERCOT. However, since this requirement does not exist in NERC standards, there is a potential gap in assessing and mitigating the operational risks of large loads. High-resolution data provided by digital fault recorders, dynamic disturbance recorders, and phasor measurement units is essential to monitoring and analyzing the performance of large loads in events involving large load loss during voltage disturbances and oscillations.

Chapter 7: Modeling of Large Loads

Numerous postmortem analyses of grid events have underscored the necessity of modeling loads with precision to accurately re-create the evolution of these events. The composite load model is the most advanced version of load modeling used for bulk system reliability analysis. EMT models of loads have also been used frequently for specialized assessments, focusing on higher frequency dynamics and harmonic evaluations. Historically, modeling efforts have concentrated on improving representations of three-phase and single-phase motors, which constitute the largest portion of system load in terms of installed megawatt capacity. However, recent years have witnessed significant growth in large load facilities that differ markedly from traditional industrial load. These new types of loads are not only substantial in size but also predominantly consist of numerous rectifiers that supply power to the end process, contrasting sharply with traditional industrial loads dominated by large induction or synchronous motors. This shift has introduced two major challenges. Firstly, existing phasor domain load models, such as composite load models, are not equipped to accurately represent large power electronic rectifier-driven loads.[97] Secondly, even if suitable models were developed, there is a lack of information necessary for engineers to properly parameterize these models. The recent events in ERCOT,[98] the EI,[99] and EirGrid[100] have demonstrated that these devices can operate in ways that put the system reliability at risk. Therefore, accurate models for these devices that reliably predict their behavior are essential for maintaining grid stability and reliability. This chapter documents industry's needs and gaps related to the modeling of emerging large load facilities.

Key Point

Even if the needed phasor-domain large load models were developed, there is still a gap in information necessary to properly parameterize the models.

Modeling Philosophy and Terminology

Before discussing modeling gaps, it is important to acknowledge that models of physical systems are never perfectly accurate. Instead, models aim to capture the phenomena of interest related to a physical system as accurately as possible to aid in decision-making through simulation studies. Furthermore, in the context of power system dynamic assessments, a single simulation platform is generally not suitable for all types of assessment; simulation tools are selected depending on the type of dynamics. The use cases of various simulation tools, as well as the common terminologies related to power system modeling and how these are applied to reliability risk assessments, are discussed in **Appendix A**. To define modeling gaps, the common terminologies related to power system modeling and how these apply to reliability risk assessments must be understood.

Gaps in Model Availability

It is worthwhile to discuss model availability gaps separately for phasor domain (or positive sequence models) and EMT models.

Phasor Domain or Positive Sequence Models

As mentioned earlier, until the past few years, the load modeling space was mostly focused on modeling single-phase residential air-conditioning systems, known to cause fault-induced delayed voltage recovery. The composite load model that is currently used by most utilities is extremely simplistic for electronic loads. The simplified electronic load model was sufficient when the majority of the electronic loads on the system were consumer electronic equipment

[97] The EV charger model developed by the Electric Power Research Institute does allow for modeling some aspects of large power electronic rectifier-driven loads. Additionally, after the initial drafting of this paper, the Power Electronic Reconnecting and Ceasing (PERC1) model was developed and is the most state-of-the-art model for large power-electronic loads. While the modeling gaps identified in this paper were accurate when the content of this paper was initially being drafted, some of the gaps may be reduced with the new PERC1 model.

[98] See *ERCOT Large Load Loss/Reduction Events 2020-2024* presentation from the December 12, 2024, NERC LLTF meeting. December 2024 LLTF meeting presentations available here: https://www.nerc.com/comm/RSTC/LLTF/LLTF_Presentations_December_12_2024.pdf

[99] See Incident Review - Considering Simultaneous Voltage-Sensitive Load Reductions

[100] See *CIGRE/IEEE Webinar – Large Loads and Their Impact on the Grid an Emerging Reliability Risk* presentation, available here: https://cigre-usnc.org/wp-content/uploads/2025/05/NGN-Webinar-May-21-2025.pdf

such as computers and televisions. However, this model is insufficient when trying to model the behavior of large loads, which are now dominated by power electronic rectifier systems. Industrial UPS systems, large industrial rectifiers such as electrolysis power supply equipment, and large power electronic motor drives have sophisticated controls; their ride-through during disturbances cannot be modeled using an electronic load component in the composite load model.

In 2022, the Electric Power Research Institute, with funding from the Lawrence Berkeley National Laboratory, developed a positive sequence model for aggregated representation of vehicle chargers.[101] This model (see **Figure 7.1**) allows some more flexibility in modeling the disconnection and reconnection of electronic loads. Some studies have used this model to investigate the impact of data center disconnection.[102] However, much work is still needed to accurately model data centers. Key gaps that need to be bridged are as follows:

- **Rectifier Dynamics Representation**: The dynamics of the rectifier are currently represented by simple first-order transfer functions in this model; this is based on the assumption that loads will have stable control and that only the slower dynamics are relevant in the positive sequence. Although validated using some lab test results for electric vehicle (EV) chargers and EMT models, it still needs to be compared against a wide array of large rectifier performances (e.g., industrial UPS, electrolysis power supply equipment) to confirm whether the simplification is appropriate.
- **Control Logic Limitations in Existing Models**: The control logic in the model was primarily designed to replicate the observed disturbance ride-through behavior in EV chargers. It may not be sufficient to replicate the behavior of UPSs or other power electronic equipment. It is also unclear whether a single model will be adequate or if multiple power electronic models are needed.
- **Cyclic Load Injection**: Some large load facilities, such as AI training data centers, have cyclic load injections that this model cannot replicate.
- **Collocated Generator and Battery Dynamics**: The model cannot capture the dynamics of any collocated generator or battery energy storage systems.
- **Library Model Availability**: Importantly, the model is not available as a library model in any simulation tool other than GE PSLF.™

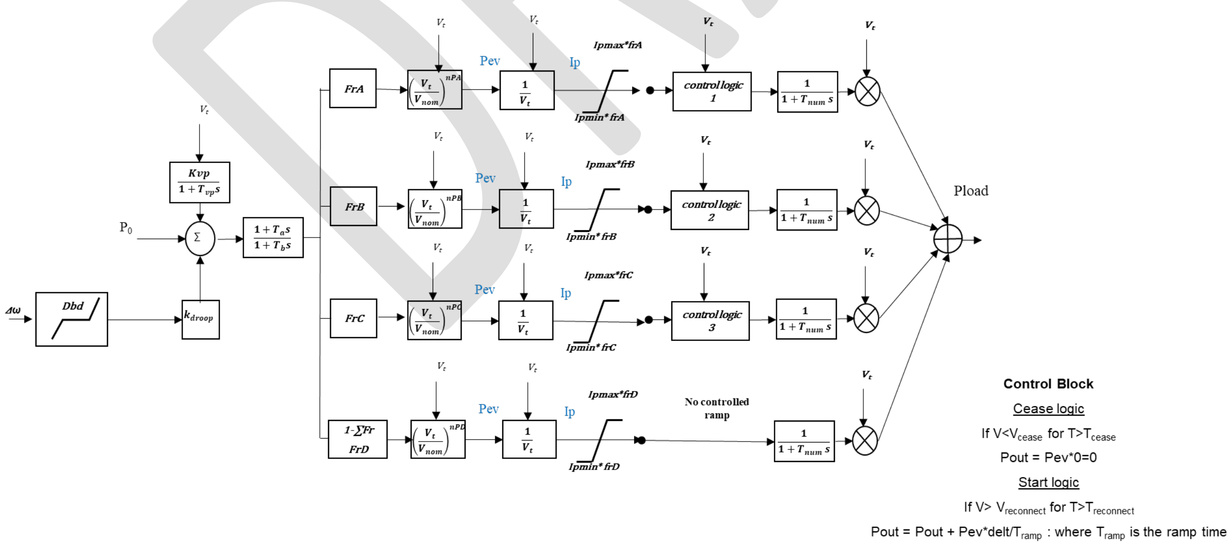

Figure 7.1: Active Power Loop for the Aggregated EV Charger Load Model

101 A Positive Sequence Model for Aggregated Representation Electric Vehicle Chargers
102 See Impact of Large Load Disconnection on System Stability 2024 Grid of the Future Symposium 1

EMT Models

Unlike positive sequence tools, EMT tools do not have library models of loads. Rather, EMT tool libraries have a wide array of motor models as well as power electronic device models that can be used to create complex load model structures. Generic structures for models are also available via some tools; these models can be customized as needed. In that respect, a particular model availability gap does not exist for EMT. However, generic structures for large load facilities are not readily available, which might present a roadblock for someone without significant expertise in EMT to create such a model on short notice.

A key gap in EMT model availability lies in the absence of standardized guidelines for modeling different components of large load facilities. For IBRs, IEEE 2800 Section G.4 provides dynamic modeling data requirements for EMT models of IBRs, including accuracy, usability, and efficiency features. For example, under model accuracy features, it specifies that sufficient detail should be included to represent the different components of an IBR plant. These requirements ensure that EMT models for IBRs are accurate, practical, and efficient for use in a wide range of studies. As another example, SPP publishes an EMT Model Requirements document that sets detailed standards for IBR models. This guidance covers aspects such as model accuracy, usability, and simulation performance.[103] However, no comparable standard or guideline exists for modeling large load facilities, which can consist of multiple UPS systems, variable frequency drives, and other power electronic components. Without clear guidance, vendors might be uncertain about the level of detail required in their developed models and could include insufficient detail, potentially reducing the accuracy and reliability of the overall facility model. Establishing standardized modeling requirements for large loads would address this gap, enabling the development of more reliable EMT models.

Gaps in Modeling Information

While the previous section discussed the unavailability of library models, another significant challenge is the lack of information about equipment in large load facilities. Traditionally, industrial load models have been developed based on survey data collected by NERC or regional working groups. For large load models, facility models have been developed based on the available literature, which is quite generic. However, the existing information is insufficient for new large facilities for several key reasons:

- **Limited Experience with Newer Facilities**: The industry lacks significant experience with newer large load facilities like data centers and hydrogen electrolysis plants. Utility engineers are often unfamiliar with the types of equipment used in these facilities to support the main processes. For example, in a data center, the UPS can operate in a double conversion mode, where the grid supply always passes through the UPS, or in an eco-mode (see **Figure 7.2**), where the grid supply is bypassed when the voltage is above a certain threshold. Similarly, for hydrogen electrolysis facilities, the power supply equipment could be either thyristor- or insulated gate bipolar transistor-based, depending on the size and type of electrolysis stack being used. These details are crucial for developing accurate models.

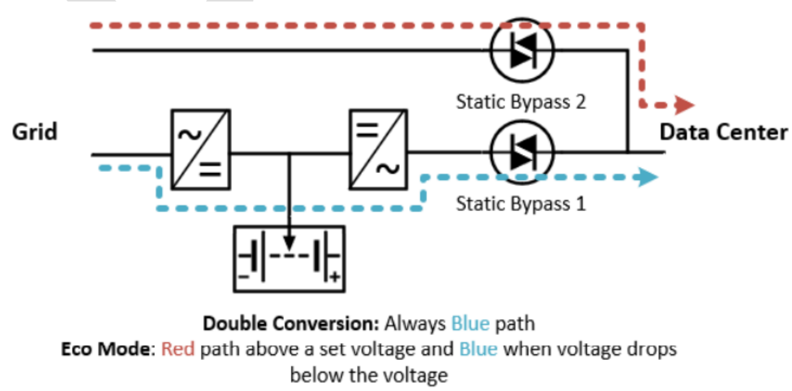

Figure 7.2: Double Conversion vs. Eco Mode Operation of Static UPS

[103] SPP EMT Model Requirements R1

- **Balance of Plant Modeling**: Apart from the main process, modeling the balance of plant, such as cooling loads for data centers and pumps and compressors for hydrogen electrolysis facilities, is essential. Information about balance of plant equipment is not readily available.
- **Highly Controllable Equipment**: Large load facilities like data centers are equipped with UPSs and other power conditioning equipment that are highly controllable and have voltage-sensitive grid disconnection thresholds. Accurately modeling the disturbance ride-through behavior of such facilities for grid studies requires TPs and utility engineers to understand how these devices detect grid anomalies and the thresholds that trigger grid disconnection and transfer of load to local backup. Such information is not readily available for inclusion in models.
- **Variable Load Patterns**: Loads such as AI training facilities create spiky (**Figure 7.3**), variable load patterns that can impact power system reliability and need to be modeled. Information about these load patterns is not readily available for inclusion in models. Furthermore, some facilities have battery energy storage systems that operate in parallel to smooth the spikes. Having information about such configurations and their control methods will be essential for developing facility models for large loads.

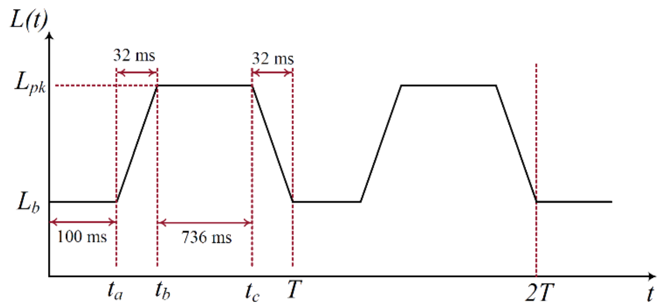

Figure 7.3: Possible AI Training Load Profile[104]

The lack of proper information presents a significant challenge for the modeling community. Without detailed information, even if models could be created, the models can never be parameterized properly for the purposes of any reasonable assessment. The gaps in modeling information are primarily due to the following:

- There are no requirements in the NERC standards specifically for load facility owners to submit validated models (or just models) to the relevant TPs. The responsibility of modeling a load facility lies with the TPs.
- Since load facility owners are not required to submit models, they might not participate in industry forums where load modeling is discussed. As such, avenues for interactions between the load modeling community and load facility owners may be very limited.
- Load facility owners may not have a clear idea as to the requirements of grid modeling. Load modeling for assessing the issues within a load facility/process is quite different than the concerns that grid engineers have and the model requirements are different.
- TOs do not always have clear data and model sharing requirements for the large loads. Additionally, large loads may be unfamiliar with utility coordination requirements.
- Large loads may be unwilling to share information due to data sensitivity concerns.

Gaps in Modeling Guidance and Practices for Large load Facilities

Since large load facilities have multiple components, guidance on how these facilities should be modeled for different studies is needed. Similar guidance has been issued in the past for modeling of wind and photovoltaic plants in phasor domain simulations. The lack of adequate guidance for modeling large load facilities needs to be addressed.

[104] Grid-Forming Inverter Applications for Improved Reliability and Power Quality in AI Data Centers

As mentioned before, EMT studies are not currently suitable for large-scale grid simulations. However, EMT studies will be increasingly important for large load facilities to ensure that the risks requiring specialized EMT modeling (e.g., resonance stability, converter-driven stability, and forced oscillations occurring at frequencies >5 Hz)[105] can be evaluated. Hence, screening methods for determining the need for EMT evaluations are necessary. Some of these screening techniques exist for IBR and HVDC interconnections that can be leveraged; however, these need to be evaluated for large load interconnections as well. Additionally, guidance on the level of modeling details needed and where aggregated modeling is acceptable in EMT simulations with large load facilities is important. The lack of adequate guidance in this area is a gap that needs to be addressed.

Traditionally, loads have not been modeled in short-circuit studies as their impact to fault currents has usually been negligible. However, the lack of representation of large load behavior during faults, particularly under weak grid conditions, may present a gap in current short-circuit and protection analysis practices. These loads can significantly impact voltage and current waveforms during disturbances, potentially compromising the accuracy and dependability of protection systems. Incorporating their dynamic characteristics into fault analysis may be important for improving the reliability and security of protection schemes in evolving grid conditions.

Gaps in Modeling Validation and Model Quality Tests

Model validation plays an important role in ensuring that the developed models are a reasonable representation of the dynamic responses of the actual devices. GOs are required to submit model validation reports on a regular basis to fulfill the requirements of Reliability Standards MOD-026[106] and MOD-027.[107] The models are validated based on staged tests[108] or based on measurements from grid disturbances.[109] Model validation has also been found to be necessary for IBRs. However, such practices are not commonplace for loads.

Load models are often validated as part of the Reliability Standard MOD-033[110] assessment; however, the MOD-033 assessment is not explicitly meant for loads but for overall system model validation. This practice was considered sufficient as loads were smaller in size and distributed across the grid. However, the advent of emerging large loads changes this assumption and model validation becomes important. For loads, model validation has a few challenges that need to be overcome:

- No standard exists today that would require a load facility owner or LSE to perform a regular model validation exercise. As such, the burden of parameterizing load models falls on TPs and is only done during the load interconnection process and fine-tuned or modified during event validation.
- Even if a model validation standard is in place, the same process as exists for generators cannot be adopted. Staged tests are generally not possible in a load facility like the exciter step response tests that can be conducted in power plants. Load model validation would then have to rely on grid disturbances. Furthermore, frequent events like single line-to-ground (SLG) faults or shallow voltage sags may not be able to excite all relevant controls in a facility to be able to model those controls.
- Proper measurement devices with desired sampling rates might not be deployed on the grid at preferred locations that would allow a modeler to isolate the response of a single facility and be able to validate the relevant models.

Model quality testing is a process used to screen dynamic models, typically IBRs, for completeness and stability before incorporating them into planning cases. The goal is not to verify a model's accuracy against real-world performance

105 See Data Center Power System Stability — Part I: Power Supply Impedance Modeling | CSEE Journals & Magazine | IEEE Xplore
106 Available here: MOD-026-1
107 Available here: MOD-027-1
108 See Automated parameter derivation for power plant models based on staged tests | IEEE Conference Publication | IEEE Xplore
109 See Power plant model validation for achieving reliability standard requirements based on recorded on-line disturbance data | IEEE Conference Publication | IEEE Xplore
110 Available here: MOD-033-2

but to ensure that it initializes correctly, responds reasonably to disturbances, and does not cause convergence or stability issues during simulation. These tests help maintain the integrity of system-wide base cases and reduce the risk of unreliable behavior in planning studies. While model quality testing is now standard practice for IBRs, there is no consistent industry approach for applying similar screening to large loads, creating a gap in how these resources are evaluated. This becomes increasingly important as fast-acting, transmission-connected loads, such as data centers, cryptocurrency mining facilities, and industrial facilities, become more prevalent and start to influence overall system behavior. Some operators have developed detailed model quality testing procedures for generators. For example, ERCOT publishes a Model Quality Guide[111] that outlines expectations for model structure, initialization behavior, simulation response, and performance under fault conditions. The process includes verification methods, such as comparison to field-measured parameters via a parameter verification report or unit model validation, to ensure that the submitted model reflects the behavior of the physical resource. These layers of screening help prevent overly idealized models from being accepted into study cases. Similar practices are not currently applied to large loads, even when their modeling could materially impact study outcomes.

[111] Available here: https://www.ercot.com/services/rq/re

Chapter 8: Risk Categorization and Mitigations

This white paper discusses the gaps in existing Reliability Standards, practices, and requirements. However, the solution to address each gap may not always be to update the specific Reliability Standard, requirement, or process that has the gap.[112] The mitigations used should be tailored based on the likelihood or severity of a BPS impact from the risk. To help determine proper mitigations for each of the risks, this chapter describes the likelihood and impact of the risks and whether those risks can be adequately mitigated by the existing registered entities. Most of the risks discussed in this chapter are based on the risks provided in Chapter 4 of the LLTF *Characteristics and Risks of Emerging Large Loads* white paper.[113] For the risks that the LLWG has determined cannot be mitigated by existing registered entities, this chapter also provides information regarding what is needed from a potential new registered entity to adequately mitigate the risk. The detailed discussions are provided in the **Risk Likelihood/Impact and Ability to Mitigate** section of this chapter.

The NERC *Framework to Address Known and Emerging Reliability and Security Risks*[114] document provides direction regarding how the risks from emerging large loads should be addressed. The LLWG recommends that this framework document is utilized to determine appropriate risk mitigations. **Figure 8.1** provides a visual overview from this framework document of the mitigations that should be used based on the likelihood and impact of a risk.

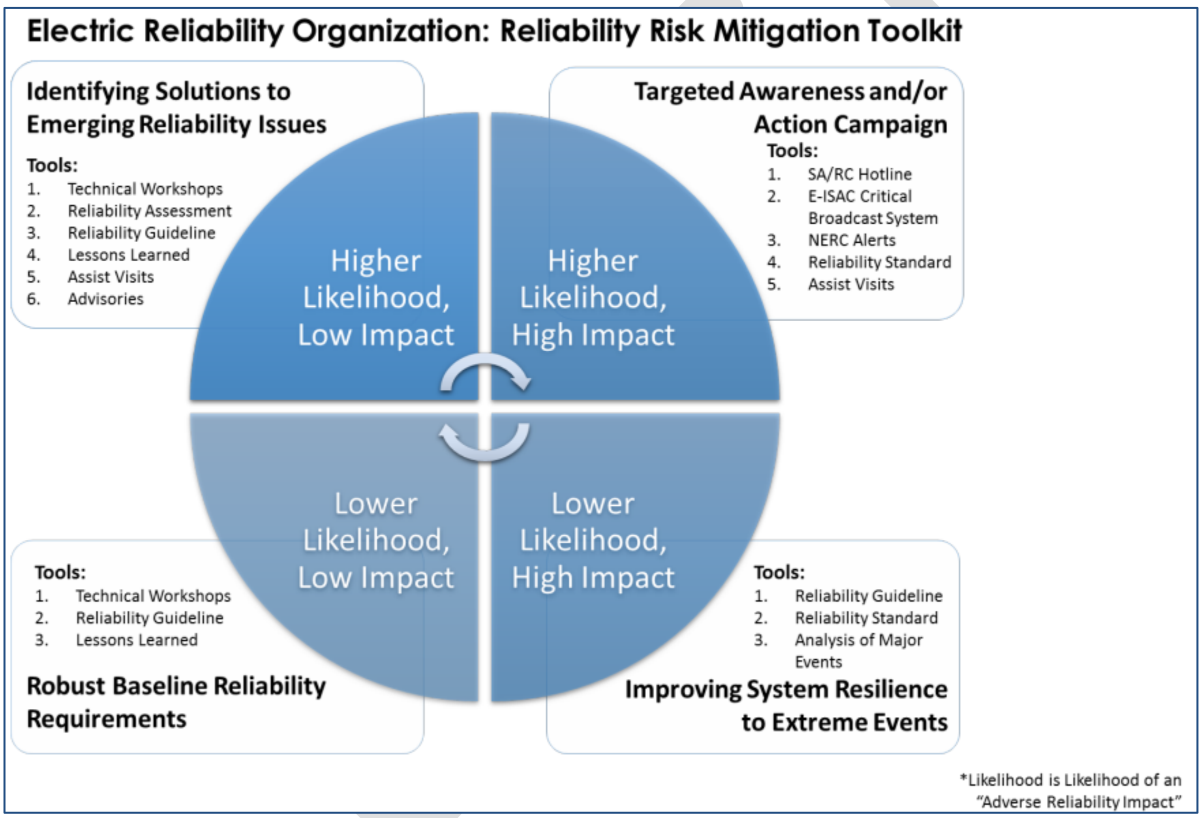

Figure 8.1: ERO Reliability Risk Mitigation Portfolio

112 For example, this paper has found that there are gaps related to emerging large loads in BAL-001, BAL-002, and BAL-003; however, accurate load modeling data and enforced disturbance ride-through requirements could help reduce the need for updates to the BAL Reliability Standards and help address risks such as voltage stability.

113 Available here: White Paper Characteristics and Risks of Emerging Large Loads

114 Available here: Framework to Address Known and Emerging Reliability and Security Risks

Figure 8.2 provides a similar figure as shown above, populated based on the findings in this chapter. The LLWG hopes that this will be useful as its recommendations are prioritized. The findings in this chapter have informed several of the recommendations provided in the Conclusion. Specifically, the risks with the following risk categorizations have been identified as needing to be addressed with Reliability Standards and this is reflected in Recommendation 2 in the Conclusion:

- High impact risks
- High likelihood risks
- Moderate likelihood, moderate impact risks

All risks discussed in this chapter, except for the System Restoration risk (which has been determined to not have any associated gaps), have been identified as needing to be addressed with Reliability Guideline(s) and this is reflected in Recommendation 3 in the Conclusion. Additionally, for the risks that existing NERC registered entities are not able to address, as discussed later in this chapter, the specific actions needed from a new type of registered entity(ies) are provided and are listed in Recommendation 1 in the Conclusion.

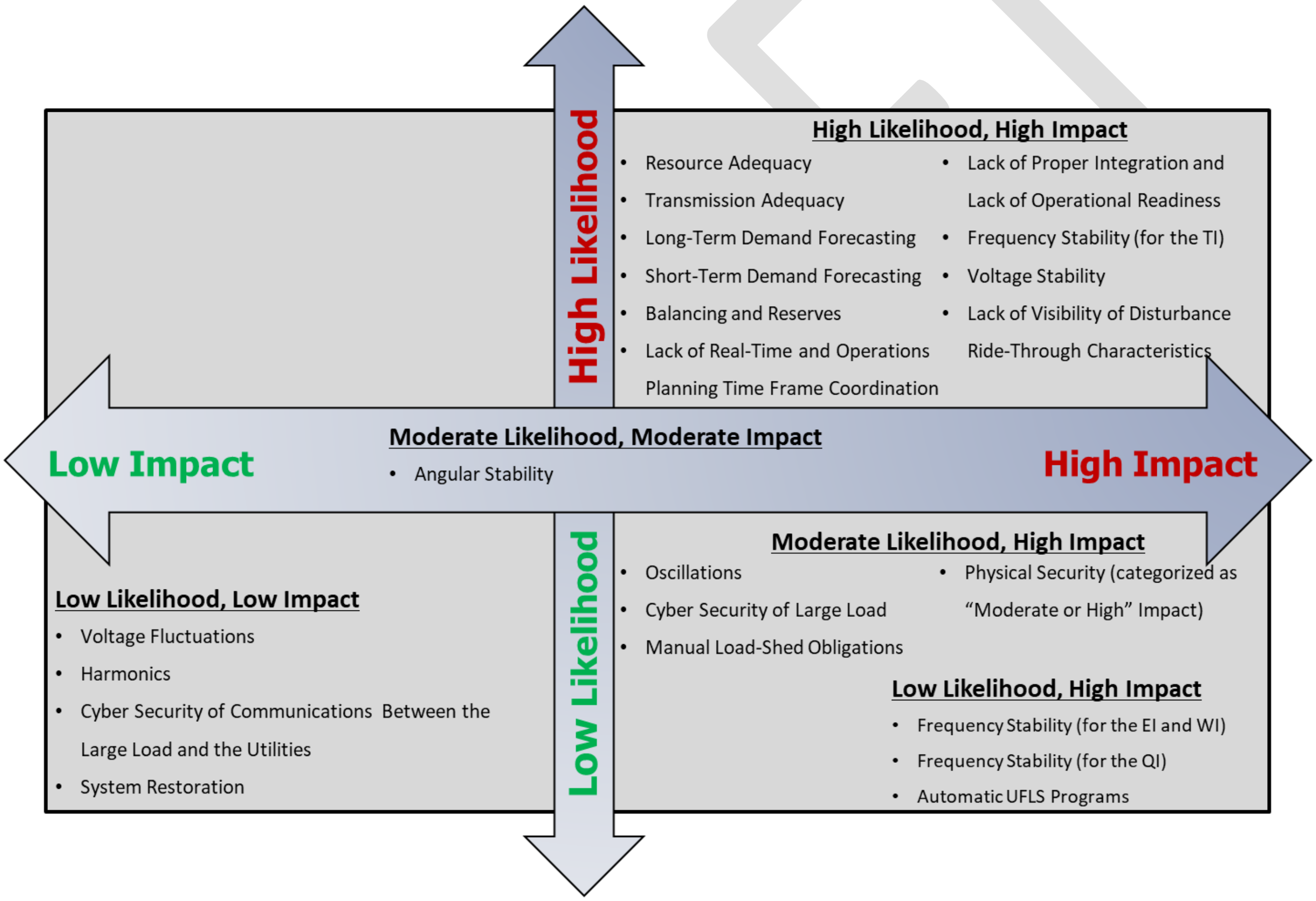

Figure 8.2: Likelihood and Impact of BPS Risks from Emerging Large Loads

For this white paper, risk likelihood and risk impact severity are defined as follows:

- Risk **likelihood** is defined in terms of the qualitative[115] probability that an event from a given risk category causes a measurable adverse reliability impact.[116] For example, harmonics are present to some extent across the entire BPS. However, this does not mean that harmonics are necessarily a high-likelihood risk—it is seldom the case that harmonics cause attributable damage to BPS equipment or result in forced outages. It is often the case that events from a particular risk category can manifest in different ways, each with a different impact severity. For example, an angular instability event could consist of a single generator disconnecting or unintentional islanding (and potential subsequent blackout) of a large region of the grid. In such cases, the likelihood rating should represent a blend of the different possible outcomes, weighted according to the impact.
- Risk **impact** severity is defined in terms of the adverse impact to the reliability of the BPS.[117] For example, an event that causes the forced outage of a single generator has a low impact, as this is a routine disturbance that the BPS is designed to withstand. On the other hand, an event that results in sudden forced outages for several dozen transmission lines has a high impact as the BPS is not designed to operate with so many assets unexpectedly out of service and may experience a collapse resulting in region-wide power outages.
- Within this white paper, there are nuances that must be handled through industry consensus among subject-matter experts. One such example is the relationship between the **duration** of a forced outage and impact severity: Whether a generator is tripped off-line by disturbance ride-through protection or because it has experienced a catastrophic turbine shaft failure, the immediate impact on the BPS is much the same—one generator is removed from service. However, the shaft failure is clearly a much more impactful event overall: The generator will be out of service for quite some time owing to repairs that require a large duration of time to implement. The capacity constraints introduced by a long-term forced generation outage can result in the BPS becoming less resilient to future disturbances. Thus, it is inappropriate to treat generator tripping and turbine shaft failure as equivalent reliability impacts.

A key consideration when determining the ability of existing registered entities to mitigate many specific risks is to determine the ability to mitigate them through interconnection requirements. Many of the requirements that are needed for large loads, such as disturbance ride-through and modeling requirements, can be placed in TO interconnection requirements via FAC-001. However, interconnecting utilities generally do not have the authority to assess performance-based financial penalties except under certain very limited circumstances. Therefore, depending on the significance of the impact from the risk, interconnection requirements may not adequately mitigate the risk; directly enforceable NERC standards may be needed instead. For generators, there are risks that are currently addressed via NERC standards, rather than only through interconnection requirements; examples of this are the frequency and voltage disturbance ride-through requirements found in NERC standards. Additionally, NERC standards provide consistent performance requirements across the BPS, while interconnection requirements can vary between TOs or regions; with that being said, interconnection requirements can have consistency if they are a result of NERC standards applicable to the TOs. A further argument supporting NERC standards being more appropriate than interconnection requirements for addressing significant BPS risks is that, if large loads, LSEs, or a similar entity do not have NERC standards directly applicable to them, the existing registered entities will then be responsible for the performance of the large loads. While this may have been appropriate for historical loads of significant size, emerging large loads are comparable to the size of significantly large generators and have unique operational characteristics, both of which create challenges for having a third party be responsible for their performance. Last, enforcement of interconnection procedure/agreement terms and conditions may vary, while enforcement mechanisms that exist for the NERC standards provide clarity.

[115] While assessments of probability are usually quantitative in nature, the assessments of risk likelihood in this chapter were developed based on the experience-based judgement of the paper contributors.

[116] Per the NERC Glossary of Terms Used in NERC Reliability Standards, adverse reliability impact is defined as "[t]he impact of an event that results in frequency-related instability; unplanned tripping of load or generation; or uncontrolled separation or cascading outages that affects a widespread area of the Interconnection."

[117] *Ibid.*

This chapter considers whether or not existing NERC registered entities can address the BPS risks presented by emerging large loads, and the language provided assumes that NERC standards are the more appropriate mechanisms for this risk mitigation for significant risks, as opposed to interconnection requirements. If it holds that NERC standards are the more appropriate mechanism, it may necessitate the registration of large loads or LSEs in order for these standards to be directly enforceable. However, if interconnection requirements are seen as being more appropriate for addressing specific gaps, the LLWG's opinion in this area may change and this may reduce the need for registration of these new entities.

Figure 8.3 provides a conceptual overview of the types of large loads that may become registered entities if, in order to address the risks posed by data centers and cryptocurrency mining facilities, (1) all large loads were registered, (2) power electronic-interfaced loads were registered, or (3) loads with a significant amount of IT equipment load were registered. As shown in the figure, registration of all large loads or registration of power electronic-interfaced loads would include other large loads in addition to data centers or cryptocurrency mining facilities.

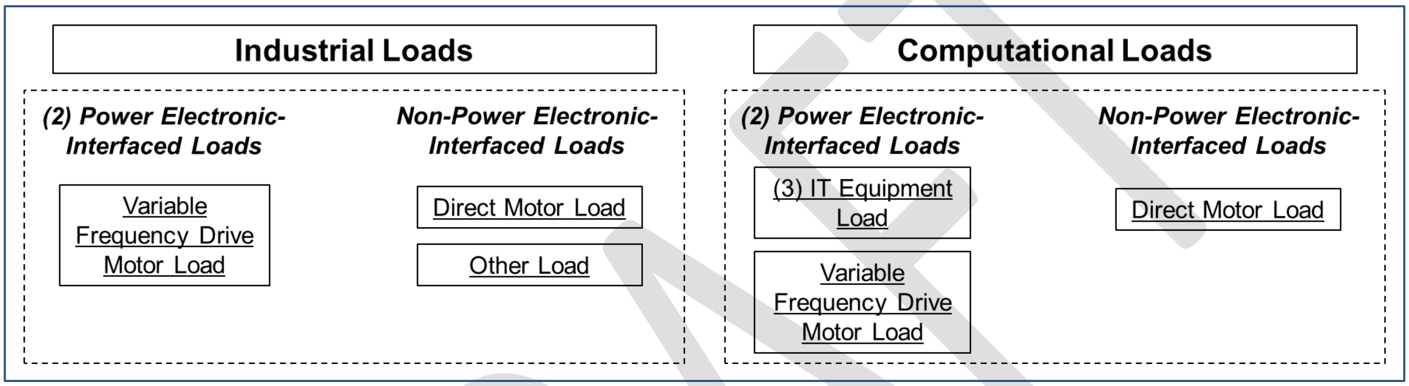

Figure 8.3: Load-Type Conceptual Overview

Risk Likelihood/Impact and Ability to Mitigate

Long-Term Planning Risks

Resource Adequacy

The impact of the Resource Adequacy risk is **high** because if the amount of load that needs to be served is close to or greater than the amount of available generation, then frequency stability may be at risk. Although work is being done in this area, many regions do not currently perform resource adequacy checks before connecting a large load. The likelihood of a reliability impact from this risk is **high** because generation can take a long time to build and data centers can come on-line very quickly. Additionally, load forecasts over the next 10 years show rapid load growth, with data centers accounting for most of the demand growth according to the 2025 NERC LTRA. Additionally, this LTRA has flagged several areas as high risk ("[i]n high-risk areas, planned resources…would result in energy shortfalls that exceed resource adequacy targets or baseline criteria for unserved energy or loss of load") starting within the next 5 years.[118]

This risk can be mitigated with existing registered entities. While information on large load location, timing, size, operational flexibility, likelihood of materialization, and other variables is needed significantly earlier than the energization date (years before the energization date), this can be obtained by existing registered entities by requiring this information with enough lead time in interconnection requirements; the TO could require that delays in the provision of necessary data by load entities result in delayed energization of load or delayed ramping of load. This information would need to be provided to the RPs by the TOs.

[118] 2025 Long-Term Reliability Assessment

Transmission Adequacy

The impact of the Transmission Adequacy risk is **high** because if the amount of load that needs to be served is greater than the available transmission capacity, then the transmission system is being run closer to its limits with respect to bulk power flows resulting in exacerbated stability risks due to increased voltage angle differences across transmission lines, increased voltage magnitude differences across transmission lines, or other factors. The likelihood of a reliability impact from this risk is **high** because large loads can come online quickly and exhibit unique system behaviors that need to be accurately modeled. Moreover, building transmission and coordinating outages require significant time, which must be studied and considered when validating the expected in-service dates of new transmission.

This risk cannot be adequately mitigated with existing registered entities. In the steady-state domain, the existing NERC registered entities have the tools to manage these thermal and voltage violations. TPs and PCs have processes in place to manage transmission expansion and resolve violations that are discovered in the planning process. During real-time operations, TOPs, RCs, and BAs can manage thermal and voltage violations by preventing load energization, re-dispatching generation, performing transmission switching, or performing load shedding. While information on large load location, timing, size, operational flexibility, likelihood of materialization, and other variables is needed significantly earlier than the energization date (years before the energization date), this can be obtained by existing registered entities by requiring this information with enough lead time in interconnection requirements; the TO could require that delays in the provision of necessary data by load entities result in delayed energization of load or delayed ramping of load. This information would need to be provided to TPs (and others) by the TOs. However, in the dynamics domain, the existing NERC registered entities do not possess the detailed information about the large load facility design and cannot build accurate dynamic models for simulations without the information possessed by large load entities. Without Reliability Standards ensuring that the dynamic modeling information provided by loads is accurate, there is concern that the information provided might not be accurate enough. Therefore, this risk cannot be adequately mitigated by existing registered entities.

To adequately mitigate the Transmission Adequacy risk, the following is needed from new type(s) of registered entity(ies):

- Provide accurate information (as accurate as possible and as early as possible) regarding large load dynamic model to support interconnection and transmission planning studies
- Inform the TP and TO and/or other applicable entities of any pertinent changes to the characteristics of the load

Long-Term[119] Demand Forecasting

The impact of the Long-Term Demand Forecasting risk is **high** because if the long-term demand forecasts are inaccurate, adequate amounts of generation might not be built to serve the load. This could result in frequency stability being at risk. Additionally, inaccurate long-term demand forecasts could lead to transmission adequacy risks. There is an influx of large loads with various amounts of certainty or uncertainty. There is not a process to determine how much of the load will materialize. The likelihood of a reliability impact from this risk is **high** because load forecasts over the next 10 years show rapid load growth, and the load forecasts are changing as well. There is a large difference between the higher and lower load forecasts, showing a large amount of uncertainty in the expected load growth.

This risk can be mitigated with existing registered entities. While information on large load location, timing, size, operational flexibility, likelihood of materialization, and other variables is needed significantly earlier than the energization date (years before the energization date), this can be obtained by existing registered entities by requiring this information with enough lead time in interconnection requirements; the TO could require that delays in the

[119] i.e., later than operational

provision of necessary data by load entities result in delayed energization of load or delayed ramping of load. This information would need to be provided to the demand forecasters by the TOs.

Operations/Balancing Risks

Short-Term[120] Demand Forecasting

The impact of the Short-Term Demand Forecasting risk is **high** because large loads such as data centers are known to fluctuate rapidly and it is known that their demand is difficult to forecast. The variability can also cause significant electricity market price impacts that can in turn impact the forecast. The large size of the load can have a significant impact on the local resource dispatch needs because of the relative size of the load compared to the area. There is also a lack of history to help inform forecasting. The likelihood of a reliability impact from this risk is **high** because large loads such as data centers are known to have varying demand and it is known that their demand is difficult to forecast. The high ramping frequency of some large loads can be difficult to capture with existing forecasting models and data processes, as well as generator automatic generation control.

This risk cannot be adequately mitigated with existing registered entities. Accurate short-term demand forecasts of large loads will likely often require the large load to participate in the developing of the forecast. This coordination could occur without requirements for the large load. However, because of the importance of short-term demand forecasts, this coordination likely needs requirements enforcing it.

To adequately mitigate the Short-Term Demand Forecasting risk, the following is needed from new type(s) of registered entity(ies):

- Provide sufficient data to applicable entities (e.g., RC, TOP, and BA) for the development of short-term demand forecasts
- Provide accurate short-term demand forecast data

Balancing and Reserves

The impact of the Balancing and Reserves risk is **high** because the large amount of demand variability that large loads such as data centers can have can lead to exhaustion of operating reserves (spinning). The likelihood of a reliability impact from this risk is **high** because large loads such as data centers are known to have rapid, unexpected demand variations. This characteristic of data centers is very well known.

This risk cannot be adequately mitigated with existing registered entities. Gaps related to short-term demand forecasting are discussed earlier in this paper.[121] Lack of accurate short-term demand forecasts for the large loads could be very impactful to the ability to balance generation and load because these loads are expected to become a significant portion of system load. However, existing registered entities cannot get accurate short-term demand forecast data.[122] Additionally, ramp rate limits on large loads, along with real-time coordination as previously discussed, are important for effective ACE management. Ramp rate limits, developed in consultation with the BA, must ensure that sufficient high-speed reserves are dedicated to managing high intra-hour and intra-minute volatility. However, because interconnection requirements do not currently require TOs to coordinate with BAs in their development, a strong mechanism is needed to obtain ramp rate limits.

[120] (operational)

[121] See Chapter 4.

[122] See the Short-Term Demand Forecasting sub-section of this chapter for more information.

To adequately mitigate the Balancing and Reserves risk, the following is needed from new type(s) of registered entity(ies):

- Provide sufficient data to applicable entities (e.g., RC, TOP, and BA) for the development of short-term demand forecasts and operating plans
- Provide accurate short-term demand forecast data
- Ensure compliance with ramp rate requirements (down ramp and up ramp)

Lack of Real-Time and Operations Planning Time Frame[123] Coordination

The impact of the Lack of Real-Time and Operations Planning Timeframe Coordination risk is **high** because a lack of real-time coordination or coordination in the operations planning time frame between the large load and the TOP/BA can lead to thermal, voltage, or frequency stability impacts if the load changes demand without coordination or begins/ends a non-forced outage without coordination. The likelihood of a reliability impact from this risk is **high** because there are no requirements in the NERC Reliability Standards for real-time coordination between large loads and BAs/TOPs/RCs. The coordination that occurs between large loads and BAs/TOPs/RCs is often inadequate.

This risk cannot be adequately mitigated with existing registered entities. Interconnection requirements can contain requirements for real-time coordination and operations planning time frame coordination. However, because this risk is a high-likelihood, high-impact risk, a stronger mechanism to mitigate the risk is needed. For example, NERC standards, in addition to interconnection requirements, are used to mitigate the impact to the BPS from IBRs. Additionally, it is essential to establish requirements for operating protocols, communication protocols, and other operational and operations planning needs based on coordination with the BA/RC/TOP. These requirements might not be adequately covered in interconnection requirements.

To adequately mitigate the Lack of Real-Time and Operations Planning Time Frame Coordination risk, the following is needed from new type(s) of registered entity(ies):

- Perform real-time (and operations planning timeframe) coordination with the TOP, BA, and/or RC, as applicable
- Adhere to necessary operating protocols, communication protocols, etc.
- Comply with operating instructions from the TOP, BA, and/or RC, as applicable and ensure appropriate training for receiving those instructions

Lack of Proper Integration and Lack of Operational Readiness[124]

The impact of the Lack of Proper Integration and Lack of Operational Readiness risk is **high** because lack of effective integration and operational readiness can lead to other high impact risks discussed in this chapter, such as Lack of Real-time and Operations Time Frame Coordination, Frequency Stability, and Voltage Stability. Examples of operational readiness can include trip settings being different than were studied and demand behavior being different than was studied, as well as other characteristics. The likelihood of a reliability impact from this risk is **high** because even without large loads, lack of operational readiness for new major BPS additions (such as new generators) is already a likely concern. Adding more large loads to the grid significantly compounds this issue.

This risk cannot be adequately mitigated with existing registered entities. FAC-001 and FAC-002 provide a framework that helps mitigate this risk, but the large load might not provide the necessary data for performing

[123] "Near-term" operations planning time frame
[124] See NERC Industry Recommendation: Large Load Interconnection, Study, Commissioning, and Operations

interconnection studies. While interconnection requirements are a powerful way to address issues, integration processes that incorporate feedback from operational registered entities are essential. Additionally, interconnection requirements can vary (by region, for example). Similar efforts are underway to increase the robustness of generation integration and validation processes. Because this risk is a high-impact risk, a stronger mechanism to mitigate the risk may be needed.

To adequately mitigate the Lack of Proper Integration and Lack of Operational Readiness risk, the following is needed from new type(s) of registered entity(ies):

- Provide TOs and/or other applicable entities with accurate information necessary for performing interconnection studies
- Coordinate with TOs and/or other applicable entities to establish a comprehensive commissioning process that ensures operational readiness
- Inform TOs and/or other applicable entities of any pertinent changes to the characteristics of the load after energization

Stability Risks

Frequency Stability (for the EI and Western Interconnection (WI))

The impact of risks to frequency stability in the EI or WI is **high** because "[t]he impact of an event that results in frequency-related instability…that affects a widespread area of the Interconnection" is an adverse reliability impact according to the NERC Glossary of Terms Used in NERC Reliability Standards.[125] The likelihood of frequency instability causing adverse impacts to BPS reliability in the EI or the WI is **low** because historical frequency response measures[126] demonstrate extreme resilience to even the largest load-loss events, coupled with a very large amount of on-line inertia historically at all times of the year.

This risk cannot be adequately mitigated with existing registered entities. Without accurate modeling data to assess the large load performance and resulting impact to the BPS, and disturbance ride-through requirements to address the impact, frequency stability may be at risk. Because this is a high-impact risk, a strong mechanism is needed to obtain these. Therefore, the existing registered entities are not able to adequately mitigate the risk. The accurate modeling data is needed to study frequency stability. The disturbance ride-through requirements are needed to help ensure frequency stability.

To adequately mitigate the Frequency Stability (for the EI and WI) risk, the following is needed from new type(s) of registered entity(ies):

- Ensure compliance with disturbance ride-through requirements
- Provide accurate load model data and ongoing model updates

Frequency Stability (for the Texas Interconnection (TI))[127]

The impact of risks to frequency stability in the TI is **high** because "[t]he impact of an event that results in frequency-related instability… that affects a widespread area of the Interconnection" is an adverse reliability impact according to the NERC Glossary of Terms Used in NERC Reliability Standards.[128] The likelihood of frequency instability causing adverse impacts to BPS reliability in the TI is **high** because a significant number of large loads are interconnecting in

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[125] Available here: Glossary of Terms Used in NERC Reliability Standards
[126] See BAL-003-2 R1
[127] Note: The TI and QI Frequency Stability risks are separated from the EI and the WI because the TI and QI are smaller Interconnections than the EI and WI, leading to different likelihood/impact considerations for these Interconnections.
[128] Available here: Glossary of Terms Used in NERC Reliability Standards

areas that already have lower system strength. Following a fault, low voltages can therefore affect a wider geographic area and increase the risk of large loads tripping, causing frequency instability. The risk is further exacerbated during conditions with low load (when grid inertia is reduced) and low IBR output, which limits downward frequency response from these resources.

This risk cannot be adequately mitigated with existing registered entities. Without accurate modeling data to assess the large load performance and resulting impact to the BPS, and disturbance ride-through requirements to address the impact, frequency stability may be at risk. Because this is a high-impact risk, a strong mechanism is needed to obtain these. Therefore, the existing registered entities are not able to adequately mitigate the risk. The accurate modeling data is needed to study frequency stability. The disturbance ride-through requirements are needed to help ensure frequency stability.

To adequately mitigate the Frequency Stability (for the TI) risk, the following is needed from new type(s) of registered entity(ies):

- Ensure compliance with disturbance ride-through requirements
- Provide accurate load model data and ongoing model updates

Frequency Stability (for the Québec Interconnection (QI))[129]

The QI, although smaller than the EI, has unique characteristics that influence the nature of the Frequency Stability risk. The Québec system operates synchronously within its own boundaries and is interconnected with other North American Interconnections through HVdc links. This configuration limits the propagation of frequency-related events to or from other interconnections. The potential impact of a frequency instability event in the QI is **high**, as in the other interconnections, since "[t]he impact of an event that results in frequency-related instability… that affects a widespread area of the Interconnection" is an adverse reliability impact according to the NERC Glossary of Terms Used in NERC Reliability Standards.[130] However, the likelihood of such events occurring remains **low** due to several factors:

- **High Inertia:** Québec's generation fleet is predominantly hydroelectric, providing significant natural inertia and frequency regulation capabilities.
- **Historical Performance:** The Québec system has demonstrated strong resilience to major load-loss events, with effective and well-managed frequency response.
- **Regulation Margin:** Hydro-Québec normally has 1,000 MW of regulation margin (up or down) at any time. This allows for responding to large load losses or variations when they occur.
- **Emerging Load Growth:** While major industrial projects are under development (e.g., electrification of processes, data centers, hydrogen production), their integration is typically well planned and supported by rigorous grid-impact studies, which helps mitigate the risk of unexpected disturbances. While the largest load on the Hydro-Québec system is about 1,000 MW, it is an arc smelter, which likely poses fewer risks to the BPS than emerging large loads such as data centers. The largest data center load in Québec is roughly 30 MW in size; Québec is not expecting data center loads larger than this to energize in the coming years.

This risk can be mitigated with existing registered entities. The risk from emerging large loads in the QI to frequency stability is not significant.

[129] Note: The TI and QI frequency stability risks are separated from the EI and WI because the TI and QI are smaller Interconnections than the EI and WI, leading to different likelihood/impact considerations for these Interconnections.
[130] Available here: Glossary of Terms Used in NERC Reliability Standards

Voltage Stability

The impact of the Voltage Stability risk is **high** because over-voltages from large load demand changes or trips can lead to tripping of nearby generation or loads, creating a cascading effect. The likelihood of a reliability impact from this risk is **high** because it is well known that many large loads do not ride through common voltage disturbances.

This risk cannot be adequately mitigated with existing registered entities. Without accurate modeling data to assess the large load performance and resulting impact to the BPS, and disturbance ride-through requirements to address the impact, voltage stability may be at risk. Because this is a high-impact risk, a strong mechanism is needed to obtain these. Therefore, the existing registered entities are not able to adequately mitigate the risk. The accurate modeling data is needed to study voltage stability. The disturbance ride-through requirements are needed to help ensure voltage stability.

To adequately mitigate the Voltage Stability risk, the following is needed from new type(s) of registered entity(ies):

- Ensure compliance with disturbance ride-through requirements
- Provide accurate load model data and ongoing model updates

Angular Stability

"The portion of the BPS affected by a particular loss of synchronism event can vary greatly, and consequences range from the outage of a single plant to the islanding of large sections of an interconnection."[131] Therefore, the impact from the Angular Stability risk is categorized as **moderate** to reflect both scenarios. The sudden disconnection of large load(s) can lead to angular stability impacts. This effect becomes more significant for loads that are larger in size. Impact is higher in areas with heavy co-location of large loads and large generators. The likelihood of a reliability impact from this risk is **moderate**. An SLG fault can cause voltage-sensitive large loads such as data centers to disconnect, leading to potential loss of synchronism of nearby generation.[132] This is notable because, without the disconnection of the large load(s), SLG faults would not usually impact nearby generation. The likelihood of angular stability-related reliability impacts due to large load disconnection is higher in areas with heavy co-location of voltage-sensitive large loads and generators.

This risk cannot be adequately mitigated with existing registered entities. Without accurate, detailed modeling data to assess the large load performance and resulting impact to the BPS, and disturbance ride-through requirements to address the impact, angular stability may be at risk. Interconnection requirements may not be a strong enough mechanism to provide these mitigations. Because this risk is a moderate-likelihood, moderate-impact risk, a stronger mechanism to mitigate the risk is needed. Therefore, the existing registered entities are not able to adequately mitigate the risk. Additionally, due to angular stability posing system-wide risks, the requirements for dynamic modeling and studies should be established on a system-wide basis.

To adequately mitigate the Angular Stability risk, the following is needed from new type(s) of registered entity(ies):

- Ensure compliance with disturbance ride-through requirements
- Provide accurate load model data and ongoing model updates

[131] White Paper Characteristics and Risks of Emerging Large Loads

[132] Note: The amount of voltage sensitivity, re-connection behavior, and system topology affect the likelihood of this risk.

Oscillations

The likelihood of a large impact (e.g., cascading or large number of generators tripping) due to large load oscillation(s) is probably low to moderate. However, the potential impact of such an event is extremely high. The likelihood of a small impact (single generator trip) due to a large load oscillation(s) is likely high because data centers are known to have oscillatory behavior and a significant portion of the overall system load in the future will be composed of large loads such as data centers. Additionally, the average size of these large loads in the future will also be very large, leading to a higher chance of impacts from data center oscillations. Because of these high-impact scenarios, the impact for the Oscillations Risk is categorized as **high.** Because the likelihood of the impact depends on the severity of the impact, the likelihood of a reliability impact from this risk is categorized as **moderate** to reflect both of the types of scenarios.

This risk cannot be adequately mitigated with existing registered entities. Existing registered entities in many areas actively monitor for oscillations in real time. It will likely be necessary for the large loads to collaborate with the registered entity to mitigate oscillations, but this collaboration can likely be achieved without Reliability Standards because the TOP has the ability to deny the large load permission to operate if it is causing oscillation issues. However, the reliability of the BPS cannot rely on detecting oscillations in real time and delayed operator response to preserve the reliability of the grid. Oscillations need to be mitigated before they occur so that they do not occur in real time. Detecting the oscillation risks before they occur is more challenging because of the lack of accurate large load model data and the fact that sub-synchronous resonance studies are very dependent on the quality of the large load models. Additionally, this risk needs to be considered on an interconnection-wide basis, not for single registered entities, as compounding frequency content injection across an interconnection can lead to severe consequences. Therefore, existing registered entities cannot adequately mitigate this risk. Large loads need to provide accurate modeling data, and Reliability Standard requirements on large loads are needed to enforce the provision of accurate load modeling data.

To adequately mitigate the Oscillations risk, the following is needed from new type(s) of registered entity(ies):

- Provide accurate load model data and ongoing model updates
- Ensure compliance with performance requirements (such as requirements from the TO, TP, or PC) to minimize and mitigate unintentional local area or interconnection-wide power oscillation interaction during normal and post-event conditions

Lack of Visibility of Disturbance Ride-Through Characteristics

The impact of the Lack of Visibility of Disturbance Ride-Through Characteristics risk is **high** because lack of disturbance ride-through can lead to frequency stability risks, voltage stability risks, or other risks. The likelihood of a reliability impact from this risk is **high** because it is well known that grid planners and operators often do not know the disturbance ride-through characteristics of large loads.

This risk can be mitigated with existing registered entities. Accurate model data for large loads is needed so that frequency stability can be accurately studied. Without accurate models, frequency stability may be at risk. This risk can be addressed by TOs if they have interconnection requirements that include model validation, model verification, commissioning testing, and other key requirements to ensure that the model data regarding disturbance ride-through characteristics is accurate.

Power Quality Risks

Voltage Fluctuations

The impact of the Voltage Fluctuations risk is **low** because voltage fluctuations (i.e., flicker) are known to not be a major issue for BPS reliability. The likelihood of a reliability impact from this risk is **low** because the likelihood of voltage fluctuations having an impact on BPS reliability is known to be low.

This risk can be mitigated with existing registered entities. This is not a significant impact to BPS reliability.

Harmonics

The impact of the harmonics risk is **low** because harmonics, even when above recommended limits, seldom cause generator damage directly impacting BPS reliability and seldom cause forced outages in BPS equipment. Additionally, the impacts from harmonics are generally localized. If it is found that harmonics, such as supraharmonics, caused by data centers cause more significant impacts to the BPS, this impact level could change. The likelihood of a reliability impact from this risk is **low** because mature and commonly used design practices and solutions exist for reducing the harmonics from electronic loads to below recommended limits.

This risk can be mitigated with existing registered entities. Interconnection requirements could address this issue. It is not a significant impact to BPS reliability, so NERC-enforceable requirements are not necessary. This can be adequately addressed with existing registered entities' policies.

Security Risks

Cyber Security of Large Load

Bad actors could induce many other high-impact risks through adversarial control which could bypass controls that mitigate other risks. If this occurred with multiple large loads, the impact from the cyber security of large load risk could be high. If this occurred with a single large load, the impact would likely be moderate. To reflect both scenarios, this Cyber Security of Large Load risk is categorized as **high** impact. The penetration of large loads on the BPS is growing, especially computational loads. Data sharing and collaboration are increasing, which increases the cyber security attack surface. Additionally, the adversaries are growing more capable. The likelihood of a high impact from this risk is low. The likelihood of a low impact from this risk is high. To reflect both scenarios, this risk is categorized as **moderate** likelihood.

This risk cannot be adequately mitigated with existing registered entities. Existing registered entities do not have adequate visibility of the large load asset owner's security protocols and practices to be able to appropriately provide requirements to mitigate the cyber security risks. Additionally, data is needed from the large load entities regarding their cyber security fabrics.

To adequately mitigate the Cyber Security of Large Load risk, the following is needed from new type(s) of registered entity(ies):

- Provide utility with site vulnerability/risk assessment and mitigate issues discovered in this assessment
- Notify utility (in close to real time) of security breaches

Cyber Security of Communications Between the Large Load and the Utilities

The impact of the Cyber Security of Communications Between the Large Load and the Utilities risk is **low** because data centers already have security practices. Existing registered entities already have NERC CIP standards in place as well. Data centers usually have tiered cyber security protection practices. Communication between the large loads and the DP, TO, TOP, BA, RC, or PC is usually going to be secure because data centers already have security practices, although the security practices may not be consistent across the industry. The tiered cyber security protection practices need to be extended out to the communication between the large loads and the utilities, and the cyber security practices for this communication should be designed in coordination with the utilities. The likelihood of a reliability impact from this risk is **low**. Some communication could be more impactful to BPS reliability, such as communication for demand response; however, this communication will likely involve more advanced security practices.

This risk can be mitigated with existing registered entities. This is a low-likelihood, low-impact risk. If needed, NERC standards can be written or modified, or guidance written, to address the cyber security risks posed by the large load to the BPS. If these standards were enforceable to existing registered entities (or the guidance addressed to existing registered entities), they could use their interconnection requirements and other processes to help ensure that the requirements in the standards or the recommendations in the guidance are followed.

Physical Security

The impact from the Physical Security risk is **moderate or high** because a physical security incident could result in some of the other BPS risks discussed in this chapter. The likelihood of a reliability impact from this risk is **moderate** because substations serving these loads may be easily accessible. Additionally, these incidents could be random targets.

This risk cannot be adequately mitigated with existing registered entities. While TO interconnection requirements could be used to help achieve the needed security protocols, lack of standardization across the BPS areas would lead to inadequate reliability. Although NERC standards applicable to the TOs could address this and the TOs could put these requirements in their interconnection requirements, the TOs may not own the substations and do not own the data centers. Physical security is not one-size-fits-all; design basis threats are used to design physical security systems and protocols. The responsibility for physical security will depend on the location. For example, the data center will have to be responsible for the security inside the data center and the TO might be responsible for the security outside of the data center (e.g., the substation).

To adequately mitigate the Physical Security risk, the following is needed from new type(s) of registered entity(ies):

- Provide utility with site vulnerability/risk assessment and mitigate issues discovered in this assessment
- Notify utility (in close to real time) of security breaches.

Load-Shedding & System Restoration Risks

Manual Load Shed Obligations

The impact of the Manual Load Shed Obligations risk is **high** because, for a situation in which a TOP or DP needs to shed a portion of a large load but the particular load is not able to be segmented, other issues, such as voltage instability, could be caused by the shedding of the entirety of the load. The likelihood of a reliability impact from this risk is **moderate** because the likelihood of needing to shed load to maintain reliability has increased due to significant generation and transmission expansion deficiencies, and a more constrained grid.

This risk can be mitigated with existing registered entities, although a more optimal solution could be reached if large loads were a registered entity.

Automatic UFLS Programs

The impact of the Automatic UFLS Programs risk is **high** because "UFLS programs are the last line of defense for BPS reliability."[133] If there is not enough load on the UFLS program, or the UFLS program does not function as expected to mitigate the frequency decline, then system-wide instability can occur, leading to cascading generator outages. The likelihood of a reliability impact from this risk is **low** because the chances of needing to use UFLS are low; historically, use of UFLS has been rare. With the current penetration, the likelihood of not having enough load on UFLS programs is low. However, with the load expected to be connected in the coming years, more load will need to be added to the UFLS programs; if load is not added, the risk may be higher. But again, the likelihood of needing to use UFLS is historically low.

[133] White Paper Characteristics and Risks of Emerging Large Loads

This risk can be mitigated with existing registered entities. Because shedding an entire large load simultaneously may cause stability concerns, there is a need to segment some large loads if they are on the UFLS program. This segmentation likely needs to be a requirement in the TO's interconnection requirements. Because this segmenting may lead to needing to have UFLS relays within the load, there may be situations where it is necessary for the large load to own UFLS relays and other related equipment. A non-registered entity owning UFLS equipment might be a risk. Therefore, the load entity might need to be registered as a UFLS-Only DP. However, none of this indicates a need to have a new type of registered entity. Additionally, there is a concern of having an inadequate amount of load on the UFLS program due to a significant amount of load being added to the system after the last PRC-006 UFLS design assessment. However, PCs can partially address this concern by reviewing their UFLS programs when large load interconnection requests are submitted to the TOs.

System Restoration

The impact of the System Restoration risk is **low** because large loads will not typically be energized early in the system restoration process.[134] The likelihood of a reliability impact from this risk is **low** because the likelihood of being in a restoration scenario is low.

This risk can be mitigated with existing registered entities. This is a low-likelihood, low-impact risk.

[134] Note: If the load was energized early in the restoration process, then this risk may be higher impact due to some large loads being known to rapidly change demand

Chapter 9: Conclusion

Addressing the Challenges and Shaping the Future

It is imperative that NERC and industry stakeholders prioritize the reliability of the grid to ensure that large loads can be connected in a reliable manner. The LLWG has identified critical reliability gaps across the lifecycle of large load integration from interconnection to long-term planning, operations, modeling, and security. Identifying and addressing these gaps will help ensure that the North American grid is ready to safely, reliably, and securely integrate these advancing technologies.

> **It is imperative that NERC and industry stakeholders prioritize the reliability of the grid to ensure that Large Loads can be connected in a reliable manner**

This white paper identified the following critical items:

1. **Opportunities to enhance NERC Reliability Standards to better accommodate large loads**
2. **Gaps in existing standards and practices concerning large loads**
3. **The lack of a registered function attributable to large loads or BPS users specifically or to LSEs**

In addition to opportunities for reforming the interconnection process at the federal or state government level, the identified gaps and opportunities could also be addressed by enhancing Reliability Standards for existing registered entities as well as updating registry criteria and Reliability Standards for large loads and/or LSEs. Updates to registration criteria are needed so that Reliability Standards can be applicable to large loads and/or LSEs. These recommended updates would support a grid that can safely, reliably, and securely accommodate large load users of the BPS.

This paper serves as a foundational step in updating industry practices to address the challenges of integrating large loads into the evolving electric grid. Alongside the LLTF *Characteristics and Risks of Emerging Large Loads* white paper,[135] it performs Step 1 of the RSTC Standard Authorization Request (SAR) Process.[136] The RSTC or others may[137] consider developing SARs or other mitigating measures to mitigate the reliability gaps discussed in this paper.

Unveiling the Critical Gaps: A Path to Reliability

The following provides a summary of many notable gaps identified in this white paper. Additional details and gaps identified can be found in the applicable sections of this paper.

Interconnection Processes and Requirements Gaps

Current interconnection processes for large loads lack standardization in comprehensive study components and performance requirements to assess reliability impacts to the grid. In many cases, large load developers or LSEs do not provide accurate modeling and operational characteristics data. As a result, TOs and TPs often study these loads with limited visibility into their performance characteristics. Additionally, NERC Reliability Standards do not require TOs to establish specific interconnection requirements reflecting the needs of their respective BAs and RCs, leading to incomplete system impact assessments. The difficulty of studying large load performance is further compounded by the accelerated development timelines typical of large load projects, which frequently outpace necessary transmission upgrades, resource construction, or operational readiness.

> **Current interconnection processes for large loads lacks standardization in comprehensive study and performance requirements to assess reliability impacts**

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135 Available here: White Paper Characteristics and Risks of Emerging Large Loads
136 Available here: RSTC SAR Development Process clean Sept 20 2023.pdf
137 *Ibid. See also*, the NERC Rules of Procedure regarding submittal of SARs.

Unlike generator interconnections, large load interconnections typically lack requirements for post-energization model validation, performance validation, or other information gathering. This results in a gap to assess real-time performance compared to planning and operational planning assumptions. Greater emphasis is needed in detailed modeling data and performance validation process to ensure that the large loads are adhering to the design and performance requirements. Additionally, there is a lack of collaboration and coordination between large load entities, utilities, and other entities. For example, there may be gaps in the coordination between grid operators/planners and the large load entities regarding important large load design decisions, such as those related to the facility's transfer to backup power supply and the return to utility during/after voltage disturbances.

Planning and Resource Adequacy Gaps

Many traditional long- and short-term planning processes may not account for the scale, uncertainty, and dynamic behavior of emerging large loads. Unlike conventional load additions, many of these facilities energize incrementally over months or years, often deviating from initial development timelines and forecasted demand profiles. Current load forecasting methods lack well-established mechanisms to incorporate these long-term load ramping profiles, the impact of behind-the-meter generation or storage, and the potential for participation in demand-response or price-responsive programs. Although not all large load interconnection requests will materialize, there is no uniform guidance across the industry on when and how large loads should be integrated into planning studies. The absence of standardized input assumptions for these loads significantly impacts the accuracy of resource adequacy assessments. This gap increases the risk of misalignment between actual system needs and infrastructure procurement, potentially leading to under-investment in generation and transmission or investing in transmission infrastructure in the wrong locations. There is an opportunity for stronger coordination among planning entities and other entities and for improved accuracy. Additionally, a potential gap in Reliability Standard FAC-002 is that there is no requirement for resource adequacy to be checked before integrating a new large load onto the system or before the peak demand of an existing large load is increased.

Many traditional long- and short-term planning processes may not account for the scale, uncertainty, and dynamic behavior of emerging large loads

Balancing and Operational Gaps

Large loads may exhibit sudden changes in power consumption under normal conditions or reduce demand during voltage or frequency excursions, leading to an imbalance between generation and load. Computational facilities are loads driven by power electronics and can be highly responsive to grid conditions and other signals. In fact, it is arguable that computational large loads essentially operate as controllable BES elements. As most large load users of the BPS are not NERC registered entities, they are not directly subject to coordination requirements with BAs (such as the requirements in Reliability Standard TOP-001). Furthermore, LSEs were also removed from the NERC registry criteria based on specific facts and circumstances approximately 10 years ago, so they are not subject to the coordination requirements with BAs. Without modifying the NERC registry criteria and Reliability Standards in order to have enforceable coordination requirements and other requirements for large loads, large load real-time operating behavior can result in ACE volatility and exhaustion of generation resources used for frequency regulation. Gaps may exist in the BAL-001, BAL-002, and BAL-003 Reliability Standards and associated processes as they do not fully address the risks related to balancing posed by large loads. For example, in the process associated with BAL-003, all BAs submit their largest credible generation contingencies, but this standard does not have a similar process for load loss contingencies. This generator loss information is used to determine the amount of frequency response required for the interconnection and for individual BAs. Operators often lack telemetry or observability into large load facilities,

As LSEs and most large load users of the BPS are not NERC registered entities, they are not directly subject to coordination requirements with BAs

resulting in a lack of situational awareness that can impact real-time decision-making. Additionally, gaps exist in requiring large loads to provide RCs/BAs/TOPs with the data necessary to perform reliable operations. Furthermore, as highly controllable and impactful facilities, gaps exist in that large loads are not obligated to establish interpersonal communication protocols with system operators nor be trained in critical reliability related tasks. Additionally, gaps may exist in the engineering practices related to checking operational readiness prior to energization of large loads. Examples of these practices include integrating new loads into modeling tools and energy management systems, and operational agreements covering communication for normal and emergency operations. There may also be a gap in IRO-017 and related practices in that this standard does not explicitly consider outages of large loads. Overall, many of the NERC standards related to planning, operations, and operations planning do not consider the impacts of large-scale ramping, disconnection, and reconnection events.

Disturbance Ride-Through, Stability, and Power Quality Gaps

Utilities do not always know the voltage and frequency disturbance ride-through characteristics of large loads, making it difficult to assess stability concerns. No existing NERC Reliability Standards provide requirements for voltage or frequency disturbance ride-through of large loads, and the lack of data on large load performance makes it difficult to study these loads. There is also a lack of coordination between existing registered entities and large loads on when a load should return to pre-disturbance demand levels after a voltage/frequency disturbance. Regarding existing registered entities, gaps exist related to the following:

Utilities do not always know the voltage and frequency disturbance ride-through characteristics of large loads, making it difficult to assess stability concerns

- Load models used and scenarios considered in transient stability studies
- Load modeling practices related to frequency and voltage stability studies
- Scenarios used for frequency stability studies.
- The impacts of large loads on UFLS and UVLS programs.

IEEE standards, such as IEEE 519, provide requirements for limiting harmonics and this standard can be applied to large loads. The limits, applicable to both voltage and current, are common to all interconnections without further coordination among them. However, the lack of coordination among different large load interconnections may create situations where individual projects are compliant with limits at their connection point but create non-compliance at other nodes in the system.[138] Furthermore, there are gaps in determining interharmonic limits.

There are also gaps in the modeling and practices related to converter-driven stability, resonance stability, and allowable limits for forced oscillations.

Security, Resilience, and Event Analysis Gaps

Large loads often deploy extensive cyber-physical systems, including private IoT infrastructure, that introduce opportunities for potential attacks by threat actors that are not addressed by current NERC CIP Standards. Because most large load facilities are not registered entities, they are not obligated to follow NERC CIP or PER Standards even though their size and connectivity may pose reliability risks. Additionally, with most not being NERC registered entities, these loads are not subject to post-event analysis reporting requirements. Large loads are also not subject to disturbance monitoring requirements in the NERC Reliability Standards; this may also be gap.

[138] In comparison, other jurisdictions, such as most European transmission system operators, provide individual harmonic emission limits to each customer enforced as part of the compliance process.

Large loads often deploy extensive cyber-physical systems, including private IoT infrastructure, that introduce opportunities for potential attacks by threat actors that are not addressed by current NERC CIP Standards

Modeling Gaps

Existing phasor domain load models do not adequately reflect the characteristics of large power electronic loads.[139] Data center UPS systems, hydrogen electrolyzer power supplies, and AI training facilities exhibit dynamic and nonlinear responses during system events. In many cases, even when a phasor domain or EMT model is developed, engineers lack the necessary parameter inputs or operational data to validate the models. EMT models may be required in weak grid conditions, but there is limited guidance or standardization on when or how to apply them to load studies. Additionally, model quality testing procedures are not used for large loads, increasing the risk of invalid or unstable models being used in planning or operational assessments.

In many cases, even when a phasor domain or electromagnetic transient (EMT) model is developed, engineers lack the necessary parameter inputs or operational data to validate the models

Risk Categorization and Mitigations

To determine the proper mitigation to address each of the gaps discussed in this paper, the relevant risk was categorized by likelihood and impact. Existing NERC registered entities cannot address many of the risks to the BPS from emerging large loads. Requirements are needed for additional entities (such as large loads, LSEs, or similar entities) to adequately address the risks, especially due to the severity of the risk.

Critical Reliability Recommendations

To ensure that large loads can be reliably integrated into the BPS, the LLWG recommends updating Reliability Standards and NERC registry criteria to reflect the electric grid of today and the future. Registry criteria for large loads and LSEs should be considered so that NERC Reliability Standards can be directly applicable. Reliability Standards modifications should be made for existing registered entities and large load entities. As discussed in this paper, many gaps exist in areas such as interconnection requirements, operations and balancing standards, and load modeling. Without updates to registry criteria, large loads and LSEs are not subject to Reliability Standards.

The LLWG recommends a combination of Reliability Standards updates, registry criteria revisions, educational material/guidance, and coordination with relevant stakeholders to help address the gaps identified in this white paper. The solution to address the gap may not always be to update the specific NERC standard, requirement, or process that has the gap. To tailor risk mitigation, the LLWG recommends a holistic and nuanced approach for the design of mitigation measures to ensure that the grid is ready to safely and reliably integrate emerging large loads. This approach needs to consider the likelihood of impact to the BPS from the risk and the severity of the impact. The NERC *Framework to Address Known and Emerging Reliability and Security Risks*[140] document provides direction regarding how the risks from emerging large loads should be addressed. The LLWG recommends that this document be utilized to determine appropriate risk mitigations. Applicable stakeholders should consider the gaps discussed in this paper and implement risk mitigations to address the risks posed by emerging large loads.

The following recommendations are offered as guidance to ensure the reliability and security of the BPS.[141]

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[139] The EV charger model developed by the Electric Power Research Institute does allow for modeling some aspects of large power electronic loads. Additionally, the Power Electronic Reconnecting and Ceasing (PERC1) model allows for modeling some aspects of large power electronic loads.

[140] Available here: Framework to Address Known and Emerging Reliability and Security Risks

[141] See Chapter 8 for an analysis of the risk categorization and mitigations that led to the Recommendations 1–3.

Recommendation 1: Because there are multiple high-impact risks to the BPS from large loads that NERC registered entities cannot adequately address, the LLWG recommends that NERC pursue registration of a type of entity (or types of entities) that is able to perform the following regarding large loads:[142]

- Provide accurate short-term demand forecast data
- Provide sufficient data for applicable entities (e.g., RC, TOP, and BA) for the development of short-term demand forecasts and operating plans
- Provide accurate load model data and ongoing model updates
- Inform the TO and/or other applicable entities of any pertinent changes to the characteristics of the load before and after energization
- Perform real-time (and operations planning time frame) coordination with the TOP, BA, and/or RC, as applicable
- Comply with operating instructions from the TOP, BA, and/or RC, as applicable, and ensure appropriate training for receiving those instructions
- Ensure compliance with disturbance ride-through requirements
- Ensure compliance with ramp rate requirements (down ramp and up ramp)
- Provide accurate information (as accurate as possible and as early as possible) regarding large load dynamic model to support interconnection and transmission planning studies
- Provide TOs and/or other applicable entities with accurate information necessary for performing interconnection studies
- Coordinate with TOs and/or other applicable entities to establish a comprehensive commissioning process that ensures operational readiness
- Adhere to necessary operating protocols, communication protocols, etc.
- Ensure compliance with performance requirements (such as requirements from the TO, TP, or PC) to minimize and mitigate unintentional local area or interconnection-wide power oscillation interaction during normal and post-event conditions
- Provide utility with site vulnerability/risk assessment and mitigate issues discovered in this assessment
- Notify utility (in close to real time) of security breaches

Recommendation 2: The LLWG and other groups should propose SARs, including a SAR for adding a definition of "large load" to the NERC *Glossary of Terms*,[143] to address the following unmitigated risks to the BPS related to emerging large loads:[144]

- Long-Term Planning Risks
  - Resource Adequacy
  - Transmission Adequacy

[142] The findings of the NERC Level 2 Alert: Large Load Interconnection, Study, Commissioning, and Operations, distributed on September 9, 2025, will likely help provide more information regarding the need to pursue registration of an entity type (or types of entities).
[143] Available here: Glossary of Terms Used in NERC Reliability Standards
[144] NERC requirements written for large loads may need to be coordinated with NERC requirements for generation, such as in the case of a generator(s) and a large load facility being co-located with a common point of interconnection.

    - Long-Term[145] Demand Forecasting

- **Operations/Balancing Risks**
    - Short-Term[146] Demand Forecasting
    - Balancing and Reserves
    - Lack of Real-Time and Operations Planning Time Frame[147] Coordination
    - Lack of Proper Integration and Lack of Operational Readiness[148]
- **Stability Risks**
    - Frequency Stability
    - Voltage Stability
    - Angular Stability
    - Oscillations
    - Lack of Visibility of Disturbance Ride-Through Characteristics
- **Security Risks**
    - Cyber Security of Large Load
    - Physical Security
- **Load-Shedding Risks**
    - Manual Load Shed Obligations
    - Automatic UFLS Programs

Recommendation 3: The LLWG should identify potential mitigations to risks posed by emerging large loads through improvements to existing planning and operations processes and interconnection procedures for large loads as planned for the LLWG's work item titled *Reliability Guideline: Risk Mitigation for Emerging Large Loads*. This guideline should address the risks discussed in Recommendation 2 of this white paper as well as the following risks:

- **Power Quality Risks**
    - Voltage Fluctuations
    - Harmonics
- **Security Risks**
    - Cyber Security of Communications Between the Large Load and the Utilities

Recommendation 4: Registered entities should coordinate and collaborate with large load entities and update their practices to address the gaps discussed in this paper. The upcoming LLWG reliability guideline will help provide guidance on addressing the BPS risks posed by emerging large loads.

Recommendation 5: TOs should coordinate with TPs, TOPs, PCS, BAs, and RCs as applicable to update their interconnection requirements in a timely manner to address the gaps discussed in this paper, including coordination

145 i.e., later than operational
146 (operational)
147 "Near-term" operations planning time frame
148 See NERC Industry Recommendation: Large Load Interconnection, Study, Commissioning, and Operations

and collaboration with large load entities. Additionally, PCs and TPs should update their interconnection study processes to address the gaps discussed in this paper.

Recommendation 6: The NERC Load Modeling Working Group should work to address the gaps in load modeling practices and scenarios to study as identified in this paper.

Recommendation 7: The NERC Security Working Group should further assess security gaps related to emerging large loads and propose mitigations for these gaps (including potential SARs).

Recommendation 8: The NERC System Protection and Control Working Group should further investigate any gaps related to system protection and control systems and propose mitigations for these gaps (including potential SARs).[149]

Recommendation 9: Federal and/or state regulators, as applicable, should consider the gaps identified in this paper and coordinate with utilities to assess whether incorporating additional interconnection requirements and/or studies are appropriate to reliably support integration of large loads. The LLWG supports federal and state efforts to enhance consistency in interconnection processes where possible. As of Fall 2025, the Federal Energy Regulatory Commission (FERC) is examining this question in Docket No. RM26-4.

Recommendation 10: State regulators should work with regulated utilities to review how new loads and planned additional generation impact existing planning and risk assessment frameworks. States may need to adjust their resource adequacy criteria and/or work with their utilities on energy infrastructure expansion.

Recommendation 11: To ensure that adequate resources are added or in place to meet the needs of the BPS, policymakers should review interactions between interconnection requirements, existing state regulations and planning processes, and regional grid operator requirements. Additionally, policymakers should work to better understand the full impact of large load integration in their jurisdiction, and review requirements for large load customers to provide operational data and information to TOs, TOPs, TPs, and other entities.

[149] This white paper discusses gaps related to system protection in Chapter 2. However, additional gaps may exist, and further work is needed to assess the extent of the gaps and provided recommendations to address the gaps.

Appendix A: Phasor/Time Domain Simulation Tools, Modeling Terminology, and Applications

The use cases of various simulation tools are provided in **Figure A.1**.

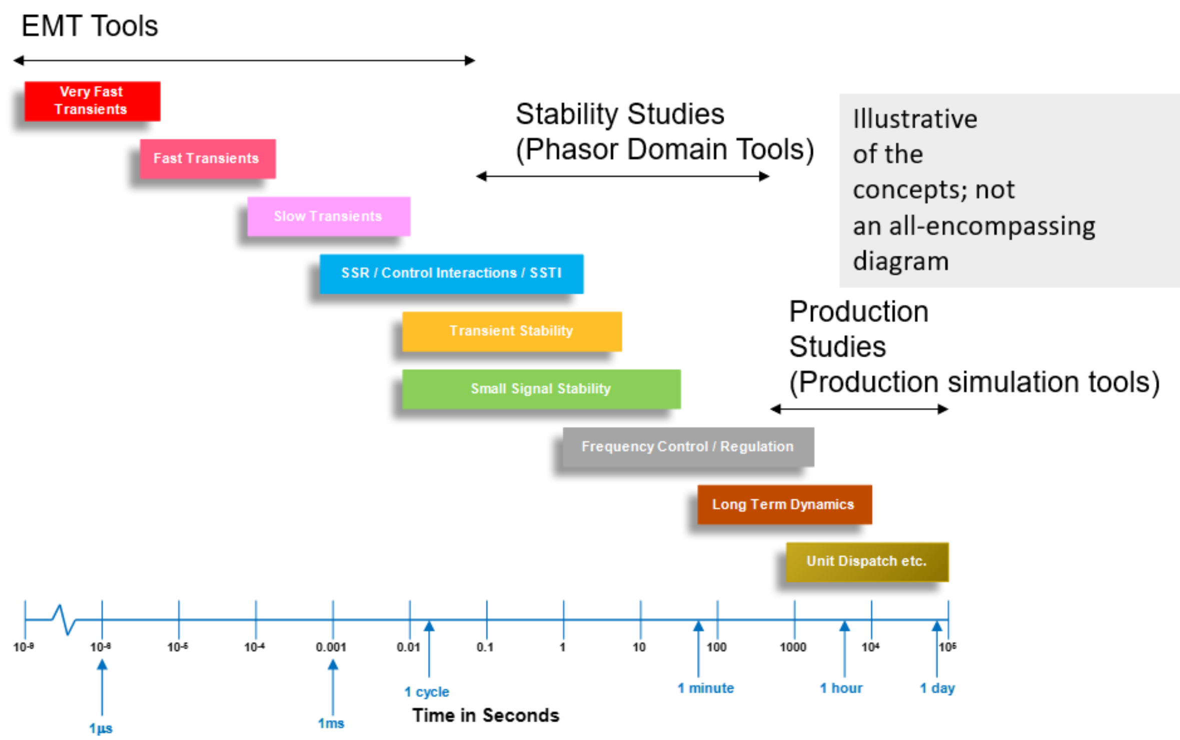

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Figure A.1: Simulation Tool Applicability Based on Dynamics Being Simulated

Terminology related to models and modeling platforms is provided below:

1. **Phasor Simulation Tools and Models:**
   a. **Purpose**: Used to study reliability risks related to slower local and inter-area oscillatory dynamics, angular and voltage stability, and unacceptable voltage and frequency excursions resulting from unexpected loss of large load during grid disturbances and unexpected load ramps.
      - **Characteristics**: These tools use simplified models to study bulk system reliability impacts, which are generally slower frequency events. Models in positive sequence platforms need to be reasonably accurate without being computationally burdensome. For example, the composite load model, with about 130 parameters, already slows down simulations for large interconnections. New large load models should not significantly add to the existing computational burden while still accurately modeling the phenomena of interest.
2. **EMT Simulation Tools and Models:**
   a. **Purpose**: Used to study reliability risks related to faster dynamics, such as subsynchronous resonances and interactions, ferroresonances, switching transients, and harmonic stability assessments.
   b. **Characteristics**: EMT models are significantly more detailed than phasor models, including faster controls and the switching of power electronic devices for certain evaluations. EMT studies typically involve detailed models of the local system connected to an external system. Due to their high level of detail,

EMT models and tools are generally not used for bulk system analysis, although some utilities maintain EMT models for their entire footprints. Most utilities use EMT studies for screened parts of the system where the reliability challenges can only be captured by modeling the faster dynamics systems, (e.g., phase-locked loop instability for weak grids, subsynchronous interactions).

3. **Generic and Original Equipment Manufacturer (OEM) Models:**

   a. **Generic Models**: Representations of power system equipment based on the basic physics of the device being modeled, covering key stability and control features common to most manufacturers. These models do not include proprietary control methods and are well documented. They are useful for long-term transmission planning studies where equipment manufacturers are not yet decided. OEMs may parameterize these models to reflect their device's dynamic performance and submit them to the relevant TP.

   b. **OEM Models**: Developed by OEMs to reflect the controls and dynamics of their own equipment, including proprietary controls. These models are often black-boxed to protect intellectual property and are submitted as user-defined library-linked models, with modeling details hidden from the TP. OEM models are used when generic models cannot sufficiently replicate the behavior of the equipment. OEM models can be in either the phasor domain or EMT.

Appendix B: NERC Standards and Applicable Sections

Table B.1 provides a list of the NERC Reliability Standards that are discussed in this paper and the paper sections (excluding the **Conclusion** chapter) in which these standards are discussed:

Table B.1: NERC Reliability Standard Discussions	
Relevant Paper Chapter	**Standard**[150]
Chapter 2: Interconnection Processes and Requirements	FAC-001
	FAC-002
Chapter 3: Planning and Resource Adequacy	BAL-502-RF
	FAC-002
	MOD-031
	MOD-032
	TPL-001
Chapter 4: Balancing and Operations	BAL-001
	BAL-002
	BAL-003
	BAL-007
	COM-001
	COM-002
	FAC-002
	FAC-011
	IRO-008
	IRO-010
	IRO-017
	PER-005
	TOP-001
	TOP-002
	TOP-003
	TPL-001
Chapter 5: Disturbance Ride-Through, Stability, and Power Quality	BAL-003
	FAC-001
	FAC-002
	MOD-032
	PRC-006
	PRC-010
	PRC-019
	PRC-024
	PRC-028
	PRC-029
	TPL-001
Chapter 6: Security, Resilience, and Event Analysis	CIP-004

[150] The NERC Reliability Standards can be found here: Reliability Standards

Table B.1: NERC Reliability Standard Discussions	
Relevant Paper Chapter	**Standard[150]**
	CIP-006
	CIP-007
	CIP-008
	CIP-014
	EOP-004
	PER-003
	PER-005
	PER-006
	PRC-002
	PRC-028
Chapter 7: Modeling of Large Loads	MOD-026
	MOD-027
	MOD-033
Chapter 8: Risk Categorization and Mitigations	FAC-001
	FAC-002
	PRC-006

Appendix C: Acknowledgements

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