Integrating Large Loads – Performance Requirements

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ESIG
ENERGY SYSTEMS INTEGRATION GROUP

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Introduction

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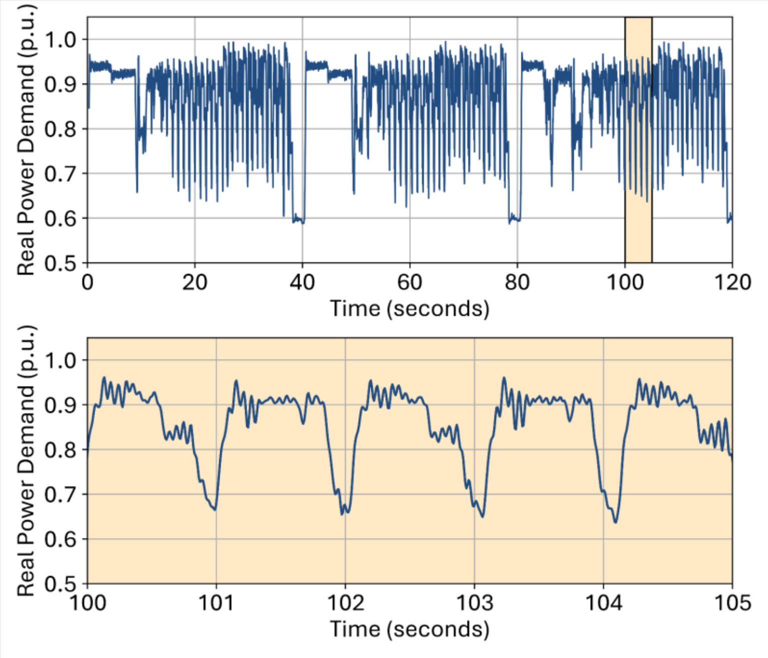
- Today, the incorporation of **new types of large loads**, particularly facilities with high proportions of **electronics**, such as data centers and crypto mining facilities, introduces new **high-impact behaviors** to the power system.

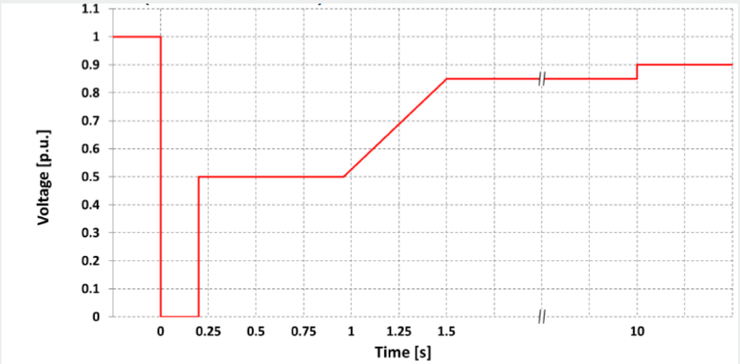
- Unlike traditional industrial consumers, these new loads feature **high power densities and rapid power fluctuations**, as well as the extensive use of power electronics that impact thermal loadings, voltage levels, voltage stability, transient stability, frequency stability, inter-area oscillations, and subsynchronous oscillations. Such stress on transmission infrastructure can **adversely impact power system reliability**.

- There is **urgency to develop and implement interconnection requirements** for large loads to avoid adverse impacts on grid reliability in the future, as well as avoid costly and technically challenging later-stage application of requirements retroactively, as the industry experienced with the interconnection of wind and solar resources

Recommended Large Load Performance Requirements

- Voltage and Frequency Ride-Through
- Active Power Recovery
- Phase Jumps
- Ramp Rates
- Cycling Behavior – Low and High Frequency
- Reactive Power Capability
- Monitoring
- Modeling





Voltage = 0 p.u. for 200 ms (bolted fault)

Sources: NERC and FINGRID

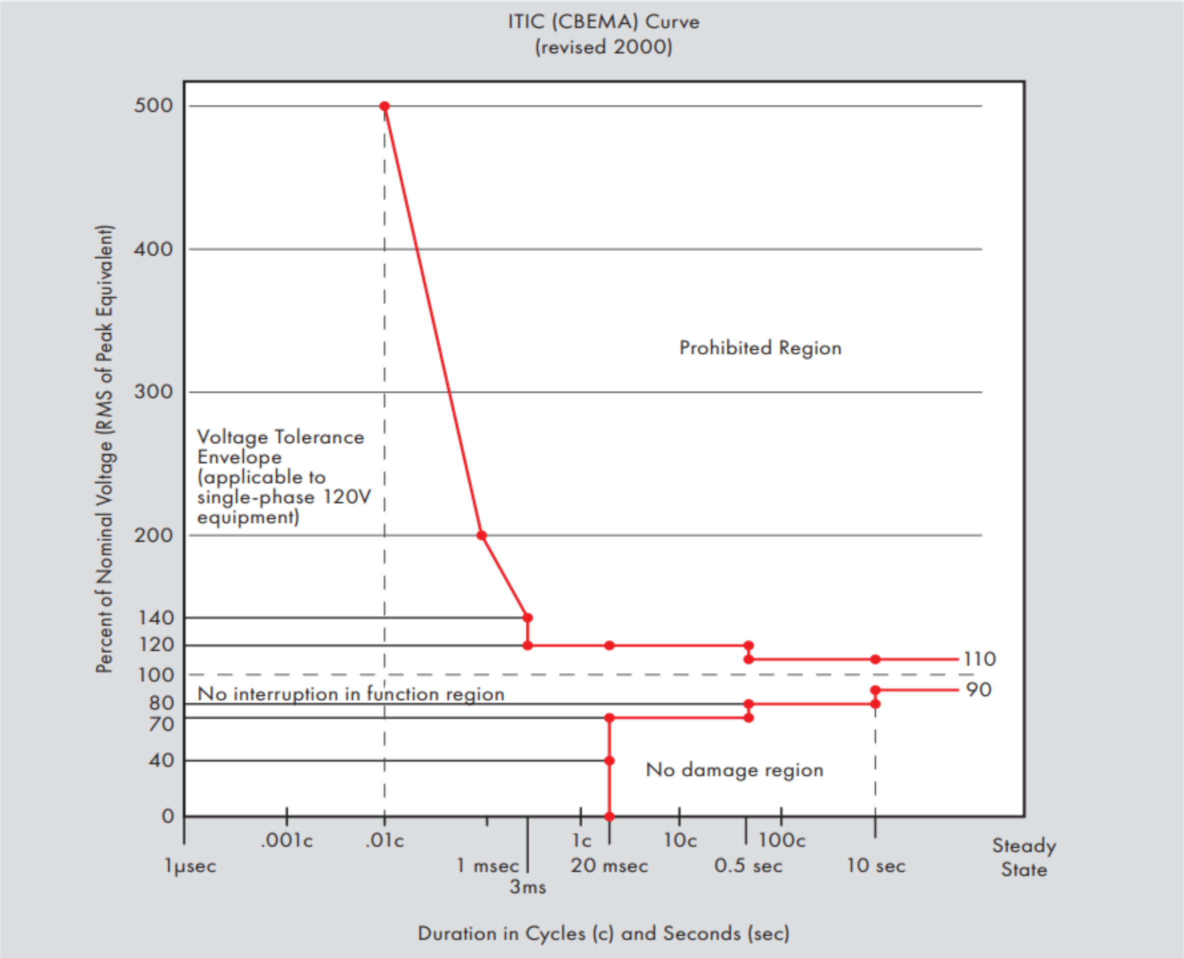
Voltage Ride-Through

- VRT is a facility's ability to remain connected to the power system during and following a disturbance.

- Facilities' inability to ride through routine contingency events could result in frequency excursions; high-voltage conditions; thermal overloads; cascading outages of generation, load, and other equipment; transient instability and/or voltage collapse; and, potentially, system-wide blackout.

- The concern with a lack of VRT capability from large loads is emerging primarily due to their size and high geographical concentrations.

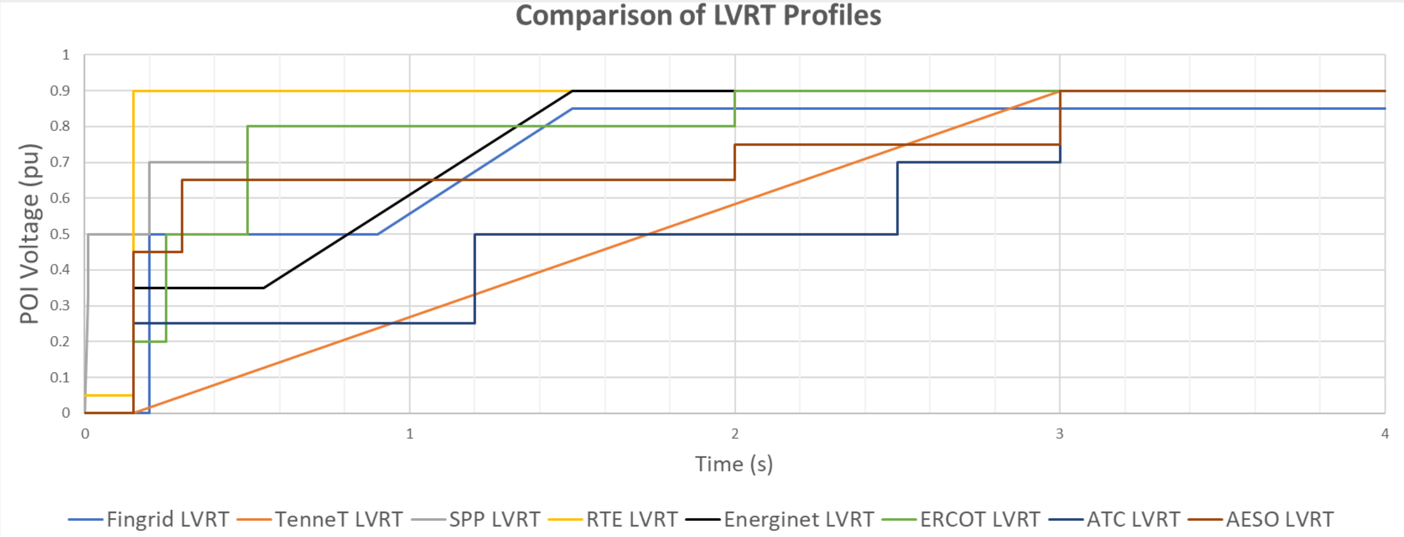
Voltage Ride-Through

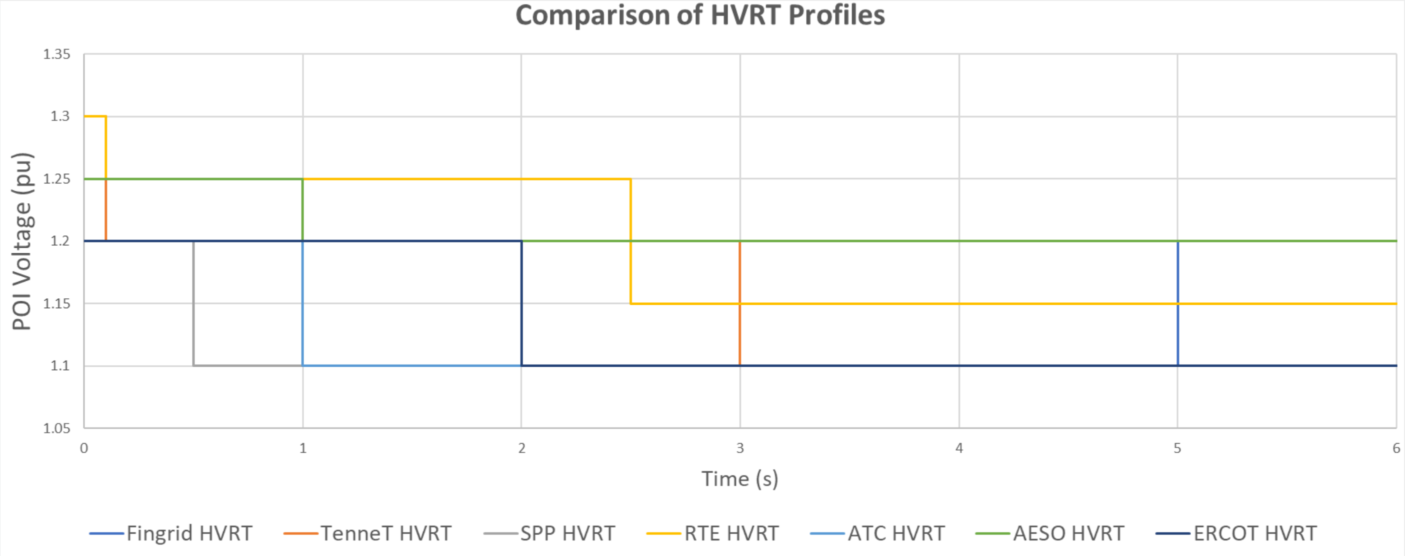


Source: Information Technology Industry Council (ITI).

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

Voltage Ride-Through





Establishing Requirements

Most large electronics-based loads are unable to ride-through recognized contingencies on the power system by design. LVRT and HVRT curves are currently being produced based on jurisdictional considerations, and there is currently no industry alignment like IEEE 2800 for IBRs.

Recommendation: Develop voltage ride-through curves for high- and low-voltage conditions based on (1) local, delayed, and remote fault-clearing times on a given part of the power system, (2) respected contingency events, (3) active power recovery timing, (4) automated post-contingency actions, and (5) normal voltage operating ranges.

Multiple Disturbance Ride-Through

Transmission System Operator, Independent System Operator, or Transmission Owner	Multiple Disturbance Events
Fingrid	Require large loads to ride-through 10 bolted faults of 100 ms each within a 90 second period
TenneT	Require large loads to ride-through 3 LVRT events within 30 minutes and 5 HVRT events within 30 minutes
Alberta Electric System Operator	Specify that the minimum ride-through durations are applicable to one or multiple faults in a 10 second window.
ATC	Require large loads to sustain 3 ride-through events over a period of 10 seconds

Establishing Requirements

Some LLs are designed to disconnect after multiple disturbances and use an event counter (e.g. three strikes rule). This can cause loads to disconnect after normally cleared faults following unsuccessful reclosure attempts, or during weather events where multiple disturbances can occur in a short period of time.

Recommendation: It is recommended that disturbance counter–based grid disconnection protections are excluded in designs or are disabled if available

Active Power Recovery

- Active power recovery (APR) requirements are **designed to facilitate load recovery** after a disturbance **without introducing** additional transient stability challenges.

- In the context of large loads, APR is the post-fault recovery of load that had been **permitted to reduce** during and immediately following the disturbance.

- In the absence of APR requirements, load might **remain at reduced** levels following the disturbance, which could result in frequency excursions; thermal overloads; cascading outages of generation, load, and other equipment; transient instability; and/or voltage collapse.

- When interconnection performance requirements include APR requirements, **post-contingency** network conditions can remain **as expected** while allowing for some load reduction needed to facilitate meeting the ride-through requirements.

Active Power Recovery

	Post Fault Active Power Recovery				
TenneT	Pre-fault active current must be restored after fault clearance.				
ATC	Active power must be fully restored within 3 cycles after the fault is cleared without shifting to back-up or UPS, otherwise detailed studies are required				
Energinet	80% of pre-disturbance power must be restored within 5s (±2% difference allowed)	90% of pre-disturbance power must be restored within 20s (±2% difference allowed)		95% of pre-disturbance power must be restored within 30s (±2% difference allowed)	
Fingrid	Datacenters: 90% of pre-disturbance power must be restored in <0.5 s	Electric boilers: 90% of pre-disturbance power must be restored in <1.0 s	Power to gas: 90% of pre-disturbance power must be restored in <1.0s	Furnaces: : 90% of pre-disturbance power must be restored in <1.0 s	Other industry: 70% of pre-disturbance power must be restored in <1.0 s
Electric Reliability Council of Texas (U.S.)	≥90% of pre-disturbance power must be restored within 1 s (when V ≥ 0.9 pu)				
Alberta Electric System Operator	Default active power recovery time is 1 s, configurable to 10 s depending on system strength.				

Establishing Requirements

APR criteria need to be established for large loads such that they facilitate recovery of load at the earliest opportunity without introducing transient stability challenges. This requires coordination with post-fault system voltage recovery after routine faults as well as an understanding of the system's capability to stabilize following the load recovery.

Recommendation: APR criteria be established considering system voltage and configurable recovery timing based on system strength. For example, large loads could be required to reach at least 90% of their pre-fault levels when post-fault voltage levels reach 0.9 pu within a default of 1 s or a specified timing based on system strength considerations.

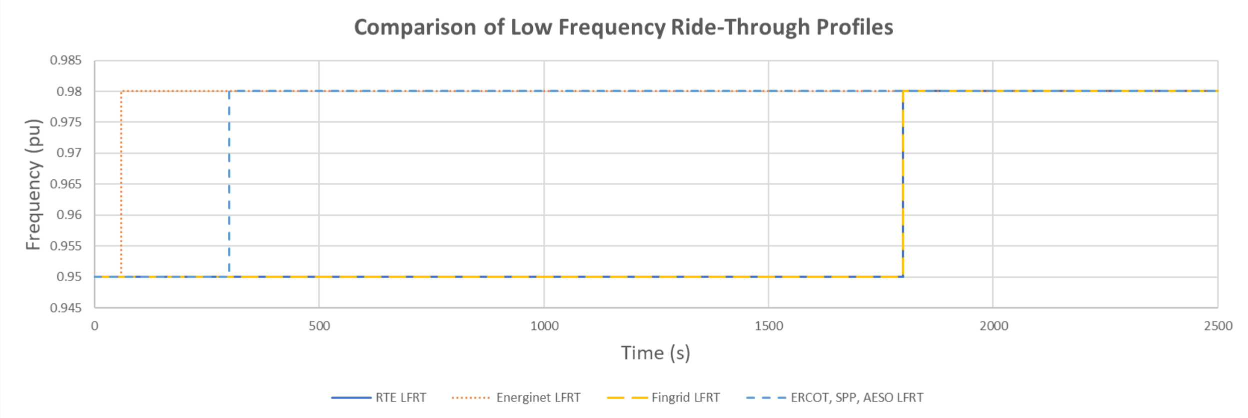
Frequency Ride-Through

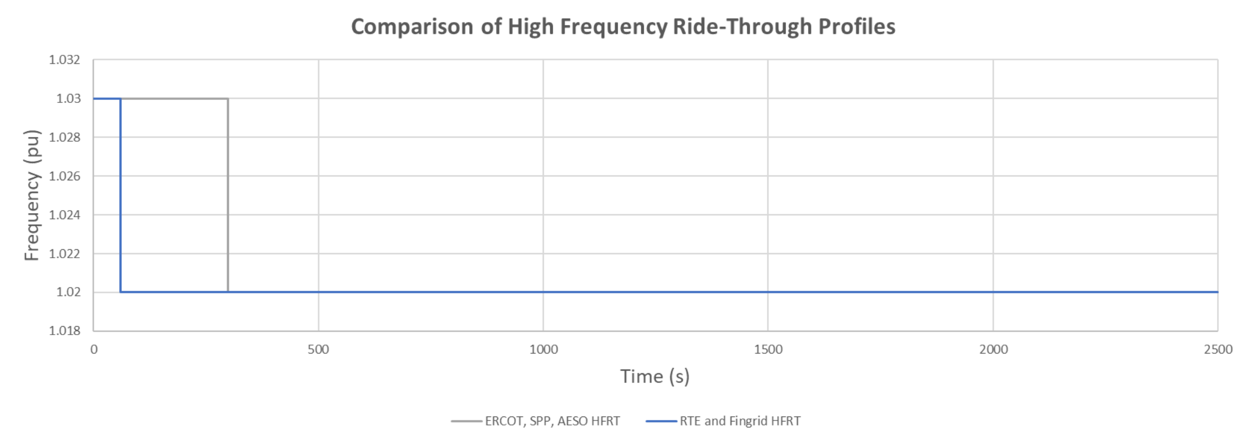
- Frequency disturbances result from system-wide imbalances between electricity generation and consumption that can propagate throughout interconnected transmission networks.

- Unlike voltage disturbances that are typically localized and confined to specific areas, frequency deviations affect the entire synchronous power system and require a coordinated response from all connected facilities to restore balance and stability.

- Frequency ride-through (FRT) requirements are intended to avoid exacerbating an initial frequency event due to subsequent disconnection of load or generation facilities.

Frequency Ride-Through





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

Recommendation

Adopt the requirements specified in IEEE 2800 and NERC PRC-029 for IBRs' frequency ride-through and RoCoF (<5/Hz/s) tolerance as minimum standards for large loads as well.

This will ensure consistent performance and continued coordinated system responses to frequency excursions, which are interconnection-wide phenomena.

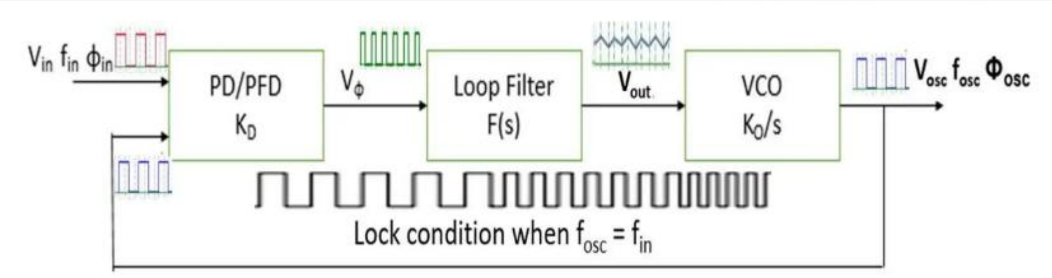
System Frequency (Hz)	Minimum Ride-Through Time (sec)
> 61.8	May trip
> 61.2	299
≤ 61.2 and ≥ 58.8	Continuous
< 58.8	299
< 57.0	May trip

Phase Jumps

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

If PLLs are unable to maintain synchronism with the AC transmission system, the large load facility will lose the ability to control active and reactive power proportions at the POI, which can adversely impact the power system.

For example, if the PLL fails to appropriately track the fundamental voltage waveform, the active and reactive power consumption could be altered to the point that results in excessive reactive current injection or withdrawal that could lead to high-voltage or low-voltage conditions, respectively.



Introduction to PLL - phase loop lock diagram | PPTX

Phase Jumps

Standard Review

In Europe, there is a varied set of requirements: ±20 degrees for Energinet, ±30 degrees for TenneT, and ±30 degrees for Fingrid. In Canada, the AESO is adopting ±25 degrees.

The other standards reviewed by the project team did not specify voltage phase-jump requirements at this time.

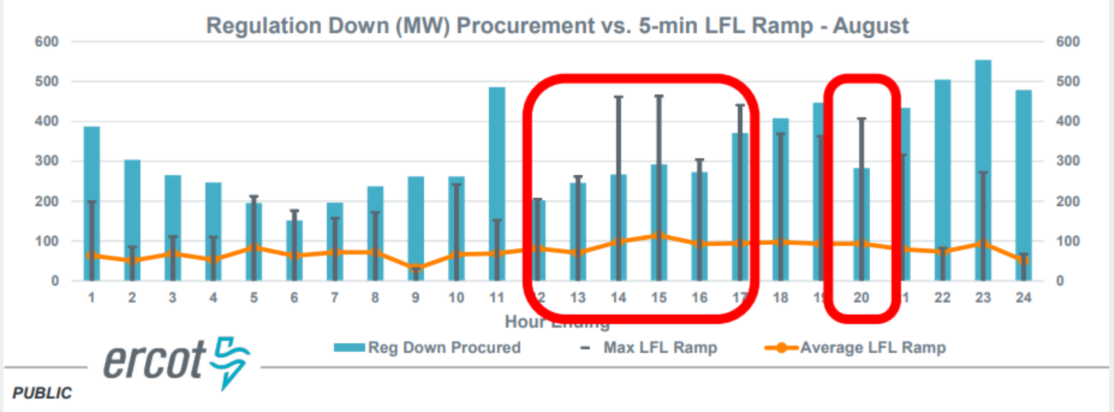
Recommendation

ISOs/RTOs and utilities can perform an initial analysis to identify the maximum voltage phase angle jump on their system for recognized planning and operational events.

If the observed phase jumps exceed the ±25 degrees established by IEEE and NERC for IBRs, a jurisdictional-specific requirement can be implemented. Otherwise, the IEEE and NERC requirement for IBRs can serve as a standard for large loads as well.

Ramp Rates

- Today, non-cyclical second-to-second active power changes related to load and generation changes are managed through frequency regulation practices, including the procurement and scheduling of resources to provide regulation services.
- Minute-to-minute changes are also addressed by regulation services, and, in addition, their cumulative impact is addressed by real-time generation dispatch at each dispatch interval.
- Specifying minute-to-minute active power ramp rate limits is essential to maintain real-time power balance (generation vs. load) and system voltages during normal grid operation.
- Without these constraints, large loads could rapidly increase or decrease their consumption, potentially causing frequency deviations if generation resources are not able to sufficiently regulate frequency and follow-load patterns.
- While this concern can potentially also be addressed with continuously reassessing and increasing regulation reserves, the trade-off between these two mitigation measures—limiting large load ramp rates versus increasing regulation reserves—has to be evaluated.



[Large Loads in ERCOT - Observations and Risks to Reliability](#)

Ramp Rates

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

Establishing Requirements

ISOs/RTOs, balancing authorities, and utilities can examine broader system-wide load-following, frequency regulation, and voltage control capabilities to establish large load ramp rate criteria, as outlined in the previous section. The collective effect of large load variability can be significantly more than that of individual facilities, and a continuous system-wide evaluation is required to ensure reliability is maintained. These analyses can factor in potential increases in frequency regulation service.

Recommendation: The results of these analyses can then be used to set ramp rate limit standards (if any) and make decisions on whether to change volumes of procured frequency regulation reserve. Operability analyses can be incorporated into planning study cycles to allow for the consideration of ramping on the determination of voltage-control devices, which could necessitate the inclusion of dynamic reactive compensation.

Low Frequency Cycling

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

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

Table 1.1: Major Modes in Various Interconnections

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

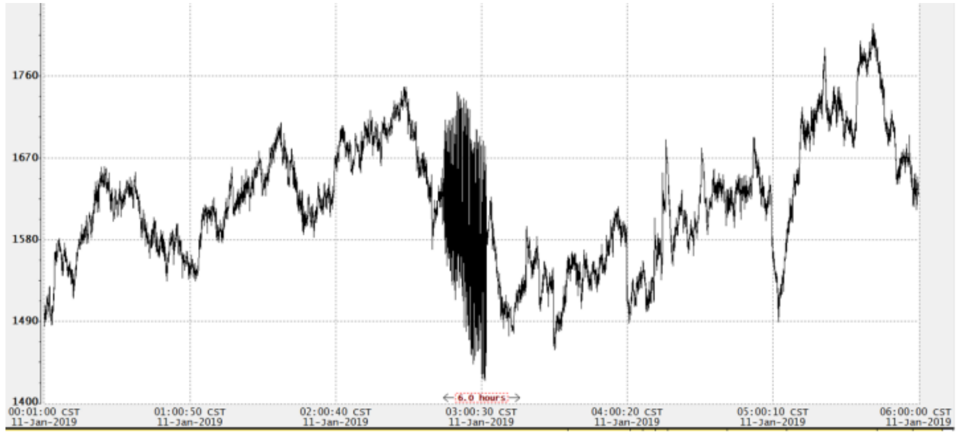


Figure A.4: Line Active Power Flow in TVA Footprint [Source: TVA]

[January 2019 Oscillation Event Report]

Low Frequency Cycling

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

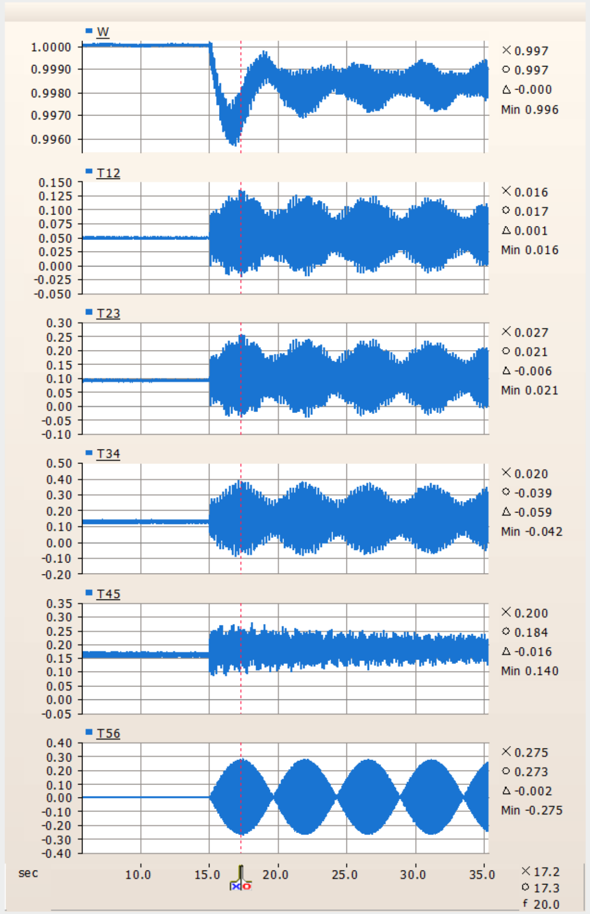
Recommendation

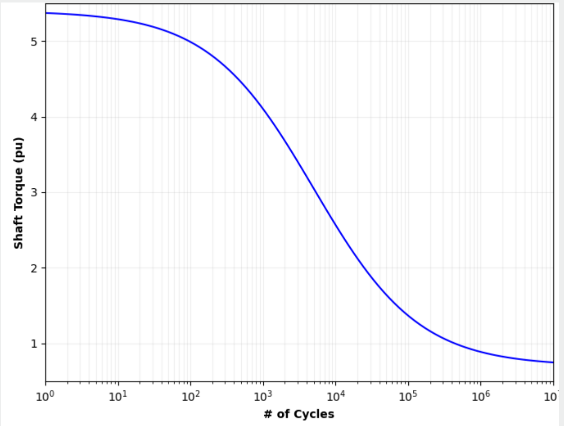
It is recommended that large loads not be permitted to introduce forced oscillations into the power system. This can be achieved by imposing requirements that significantly limit magnitudes and frequencies of forced oscillations.

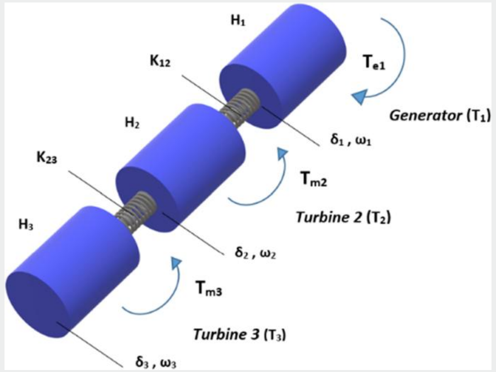
If there is residual low-frequency cycling behavior that cannot be mitigated, or if the ISO/RTO and utility accept low frequency cycling, then requirements should be established to prevent the introduction of forced oscillations at frequencies and amplitudes of concern for major known interconnection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

High Frequency Cycling

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







High Frequency Cycling

- The Alberta Electric System Operator (AESO) stipulated that large load facilities must be designed to avoid amplifying or contributing to oscillatory modes, including in the subsynchronous and torsional frequency ranges of 3 Hz to 60 Hz. The AESO further requires that forced oscillation variability be limited to less than 16 kW/100 ms, with a total change limit of 160 kW permissible.
- Fingrid's standard states that large load facilities must not cause amplification (negative damping) of power oscillations or cause cyclic power fluctuation. This includes in the 1 Hz to 15 Hz range for voltage fluctuations related to controller interactions with IBRs and resonance frequencies/torsional interactions in the 5 Hz to 45 Hz range.
- The American Transmission Company (ATC) limits load active power oscillations for large load facilities over 200 MW to 25 MW over a period of less than 5 seconds.

Establishing Requirements

A study-based approach can be leveraged to identify frequencies and amplitudes of concern that should be prevented in large load cycling profiles.

Recommendation:

- Prevent the introduction of forced oscillations at frequencies and amplitudes of concern for sub-synchronous phenomena.
- Better to not permit or significantly constrain the introduction of forced oscillations

Monitoring

- Power system operators need **high-resolution measurement** and monitoring equipment at generator and large load facilities to **accurately capture fast electrical phenomena** that cannot be seen with conventional supervisory control and data acquisition (SCADA)—such as sub-cycle voltage and frequency excursions, converter control interactions, and rapid changes in active and reactive power.

- These high-granularity data streams give operators the **visibility required to validate models**, **diagnose abnormal behavior**, and ensure that both generation and large loads remain compliant with performance requirements during disturbances, thereby supporting reliable system operation as the grid becomes increasingly power electronics–dominated.

Monitoring

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

Establishing Requirements

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

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

Q & A