Large Data Center Load Study Considerations

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Types of Large Loads: Hyperscale Cloud

- Purpose: IT resources for shared use across the internet.
- Owned by: Cloud service providers (CSPs)
- Size: 10’s to 100’s of MW
- Examples:
  - Amazon Web Service (AWS), Google Cloud Platform, Microsoft Azure
  - Netflix, Amazon shopping, Office 365, Google search, etc.
- Interface Hardware:
  - Cooling by Variable Speed Drive, sometimes with active filter
  - IT infrastructure behind distributed power distribution, behind UPS
  - Office lighting and admin computing
  - Diesel generator backup

Types of Large Loads: Crypto Mining

- Purpose: Calculation of Bitcoin, Ethereum, and other Cryptocurrency tokens.
- Owned by: Private developers
- Interface Hardware:
  - Cooling by natural wind or forced air
  - IT infrastructure behind small power supplies (no UPS)
  - No generator backup

Types of Large Loads: AI Inference

- Purpose: Distributed user requests to access trained models.
- Owned by: Private developers or Hyperscale AI
- Size: 100's MWs to >1GW
- Examples:
  - Google gemini search, GPT user requests, etc.
- Interface Hardware:
  - Similar to hyperscale cloud computing, but potentially lower reliability requirement (eg. may use UPS)

Types of Large Loads: AI Training

- Purpose: Training major AI models for use in inference.
- Owned by: Private Developers or Hyperscale AI
- Size: 100's MWs to >1 GW (in aggregate up to 5 GW)
- Examples:
  - Microsoft, Oracle, xAI, Amazon, Meta
- **Key Feature: Variable active power output.**
- Interface Hardware:
  - Same as AI Inference

Background: Large Load Characteristics

- AI training processes can exhibit fast variation in active power.
- Data center loads are not designed to ride through system events (UPS doesn't count)
- Loads are a mix of types of converter based interfaces

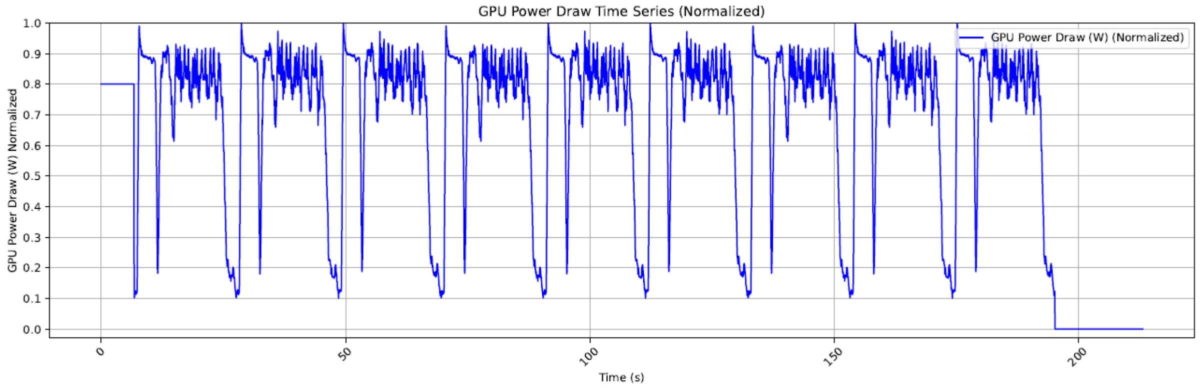

Fig. 1. Power readings from an at-scale training job on DGX-H100 racks.

Power Stabilization for AI Training Datacenters

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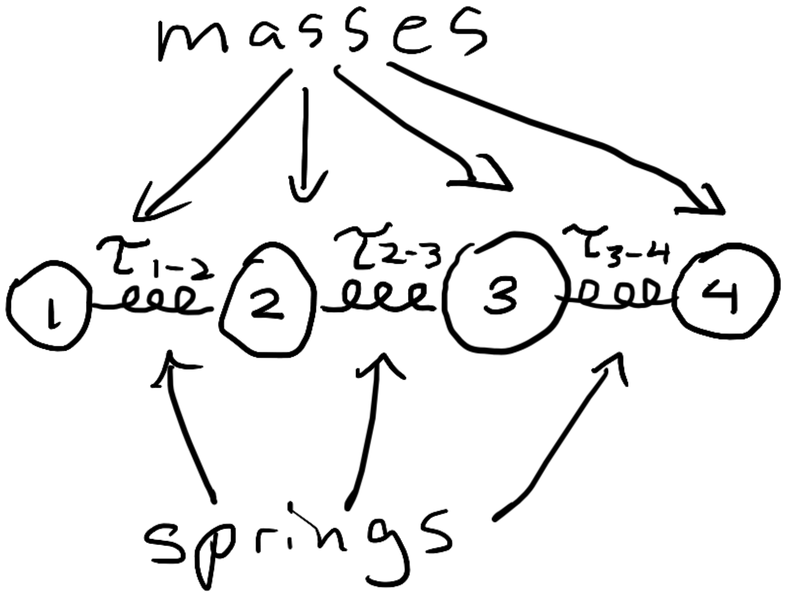
Summary of reliability risk categories

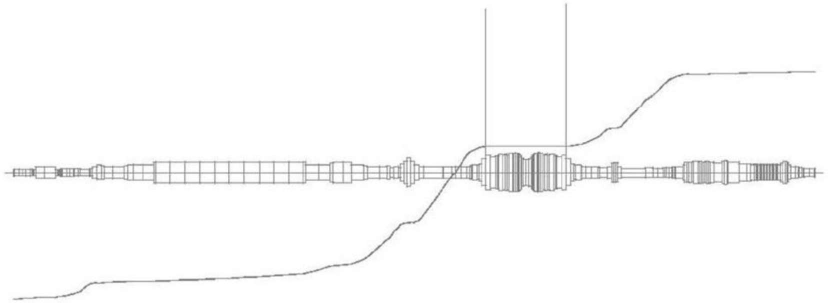
- The following are categories of risk that may drive requirements and/or studies:
  - **Basic powerflow considerations**
  - **Active power variation**
    - Synchronous generator damage
    - Flicker
    - Machine mode oscillations
    - Interarea oscillations
  - **Ride-through failure**
    - Load rejection overvoltage
    - VAR adequacy
    - Resource adequacy
  - **Passive damping**
    - SSCI instability

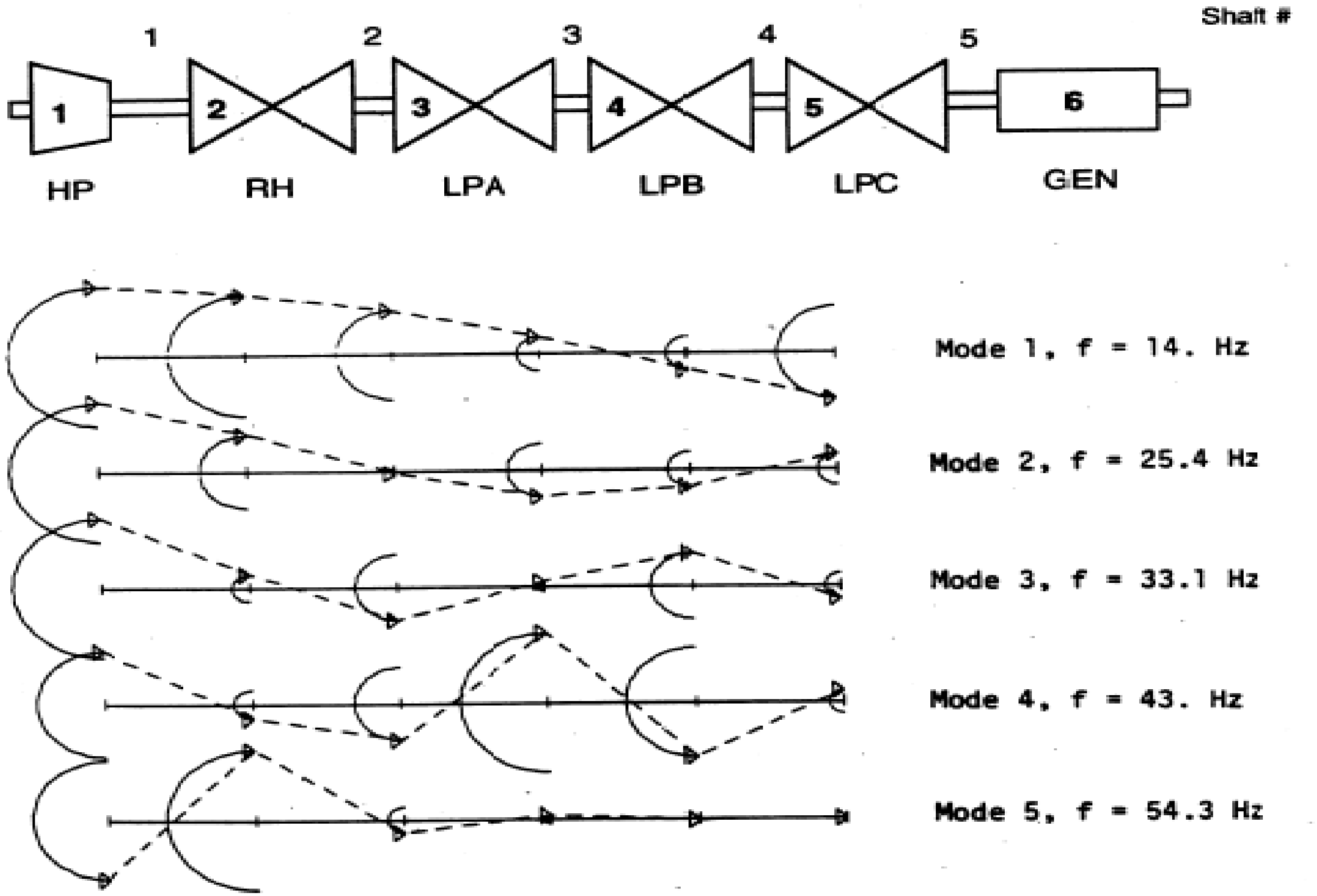
Basic Powerflow Studies:

- **Ensure the following:**
  - Sufficient generation exists (careful with “imports will handle it”)
  - Can serve the full load under outage conditions
  - VARs available to control the voltage for various transfer scenarios
  - VARs available for fast changes in load

Reminder… Synchronous Generator Shaft



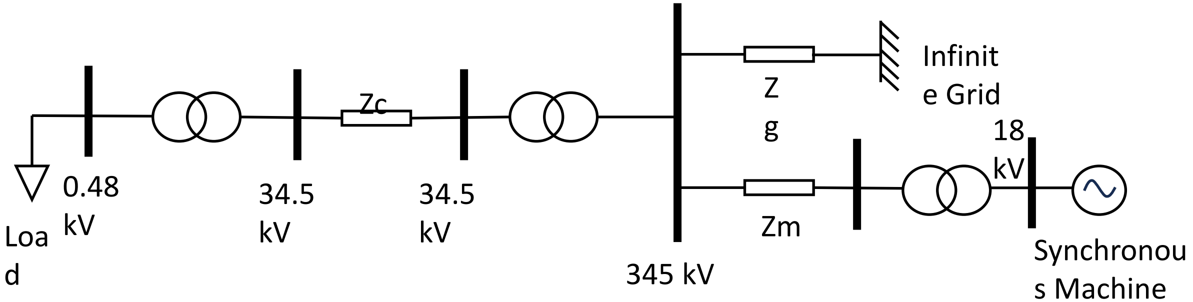




Active Power Variation Studies:

- **Synchronous generator damage risk evaluation:**
  - EMT simulation is required
  - Model detail of synchronous machine shaft system
  - Use various load profiles to force oscillations into the grid, including components of torsional frequencies
  - Measure generator shaft torques and terminal active power variation
  - Compare the torque and active power against machine long term capabilities
  - Alternative: compare load output power against variation criteria.
  - **Data Required:**
    - Synchronous machine shaft models
    - Range of potential load profiles
    - Detailed grid model
    - Mechanical and electrical limit data for machines, or requirement criteria

Example (ERCOT study)



Key Parameters:

- Machine Rating = 100 MW
- **Synchronous machine key torsional mode: 12 Hz**
- Load profiles:
  - Profile 1 (S1 – S8): Fixed frequency square wave varying between 25 MW and 100 MW with a ramp rate of 10 MW/1ms
  - Profile 2 (S9 – S16): Proxy waveform mimicking measured AI training load profile

Scenario No.	**Load Variation**	**Max Pk-Pk Active Power Variation* (Generator electrically close: Zm = 0)**			**Alternating Torque**	
		At the Load	**At the Machine**	**At the Grid**	**Tau12 (pu)**	**Tau23 (pu)**
	Hz	**MW**	**MW**	**MW**		
S1	Load profile 1 at 2 Hz	76.81	32.98	77.81	0.233	0.234
S5	Load profile 1 at 12 Hz	77.61	11.89	82.55	5.124	5.028
S9	Load profile 2	85.55	6.21	87.44	0.042	0.042
S13	Load profile 2 with 12 Hz oscillations	88.86	8.09	92.22	0.993	0.974

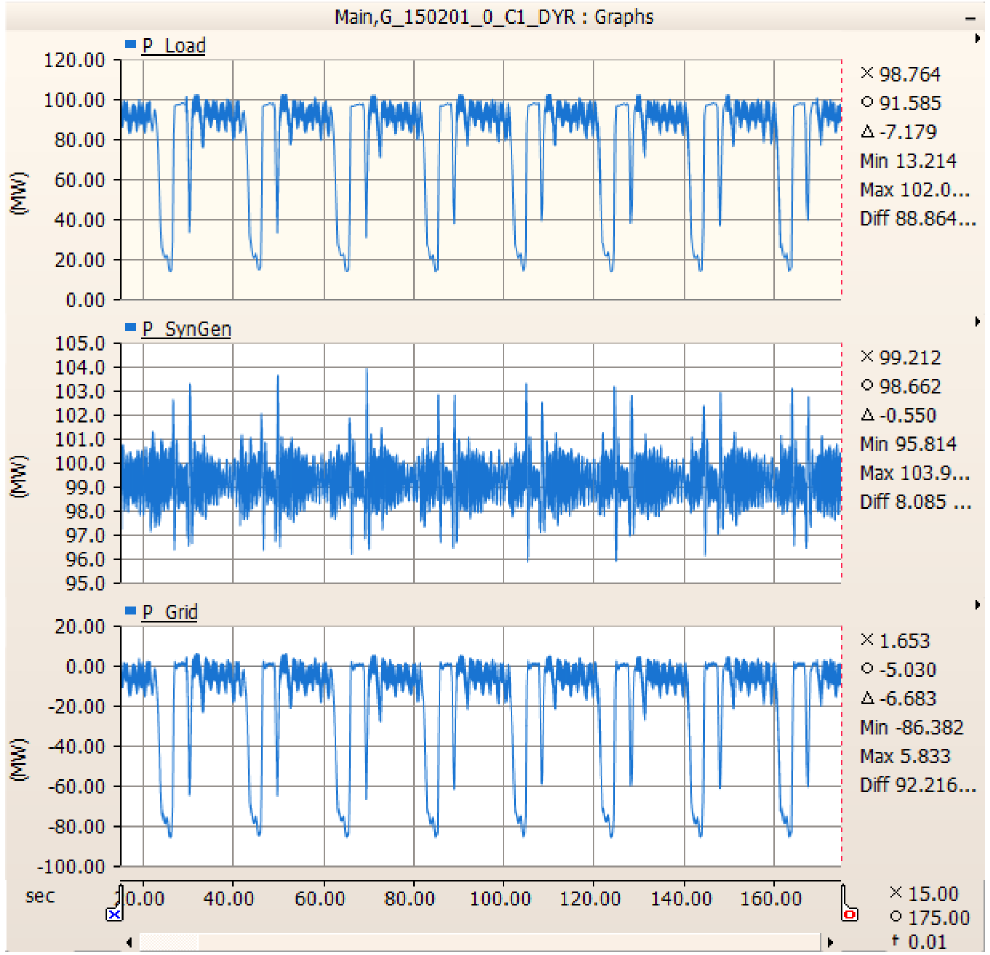
**Note: Split of active power between machine and grid is initially determined by impedance split, and the final variation will depend on the frequency of the variation and other machine characteristics over time. Ref. ERCOT LLWG October 24 meeting:*

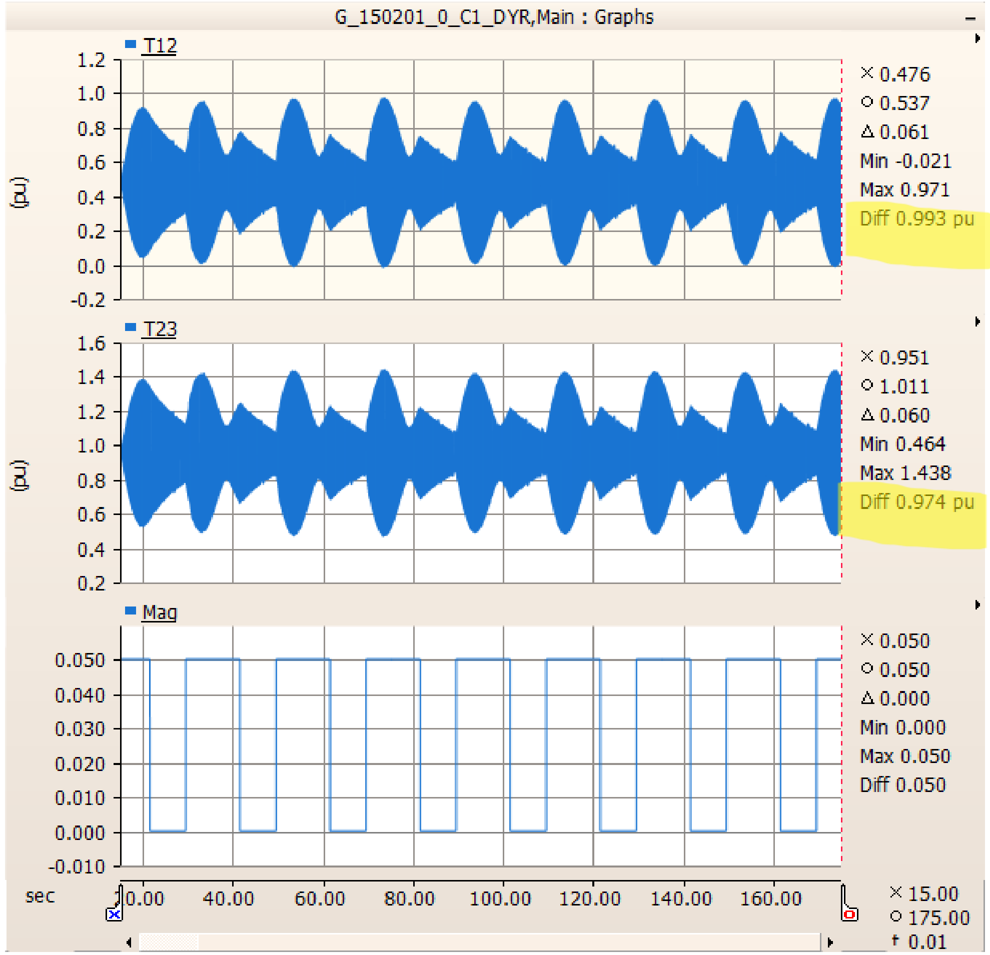
Load profile 2 with 12 Hz – Scenario S13 (similar to paper on slide 6) **1pu Torque… strong Torque Amplification!**

P Load

P Gen

P Grid





Torque 12

Torque 23

Per unit 12 Hz Component

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Some additional study challenges

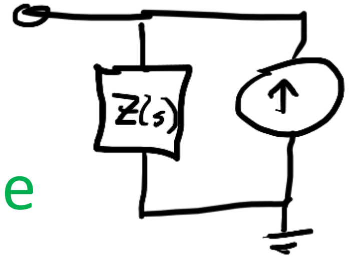
- Data is **very hard** to get for load
  - Limits on load variation
  - Harmonic profiles
  - Sufficiently detailed models to quantify damping
  - Ride-through capability
- Data is **very hard or impossible** to get for synchronous machines
  - Multi-mass data
  - Physical design limits
- Studies require specialist skills (EMT experts with special training)

Active Power Variation Studies: Flicker

- **Flicker:**
  - EMT simulation may be required
  - Flicker can be evaluated simply using powerflow tools (worst case)
  - Flicker can be more precisely quantified using simulated flicker meters
  - **Data Required:**
    - Synchronous machine shaft models
    - Range on load profiles, particularly ramp rates, magnitudes, and frequency content limits
    - Measurements are useful

What about harmonics?

- Some events were recorded of large harmonics associated with data centers…
- What is needed is a frequency dependent Norton equivalent source
- Perturbation techniques can be used to derive impedances, and currents can be measured in strong testbeds (EMT and/or site measurement)



Study!

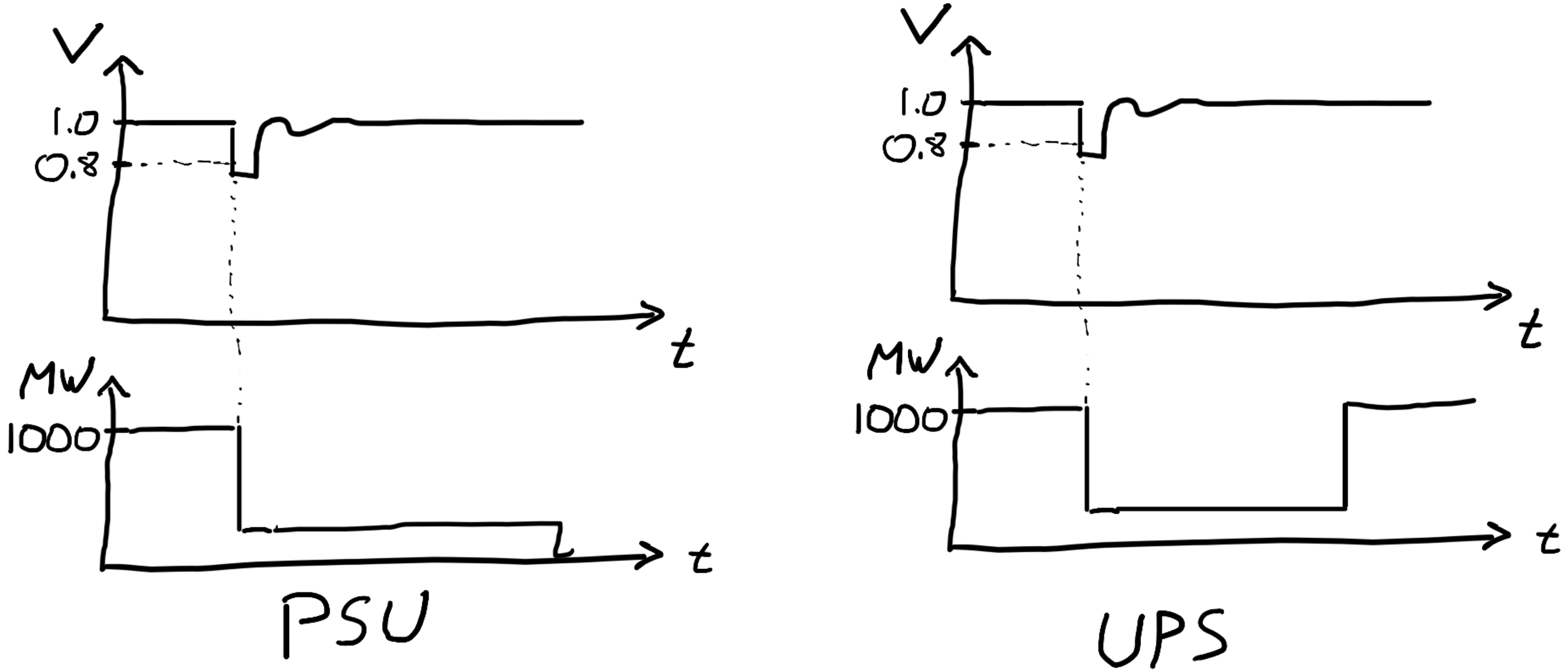
- Frequency-dependent impedance characterization is done for the external system under many operating conditions
- Harmonic sources are added
- *Multi-port* harmonic “powerflow” is calculated to create a family of possible voltage amplifications, add existing measured background harmonic voltage distortion, and check harmonic voltage distortion, and harmonic current ratings of equipment

Active Power Variation Studies:

- **Machine mode oscillations and interarea oscillations :**
  - Phasor domain (transient stability) tools are used to force the load at key machine or system modes
  - **Special data required:**
    - Transient stability models for load with flexible variation profiles
    - Range on load profiles
    - Detailed grid model
    - Data on machine mode frequencies
    - Data on interarea mode frequencies and drivers for oscillations (if interarea oscillations are being studied)

Ride-through background…

- Small voltage depressions may lead to load disconnections…

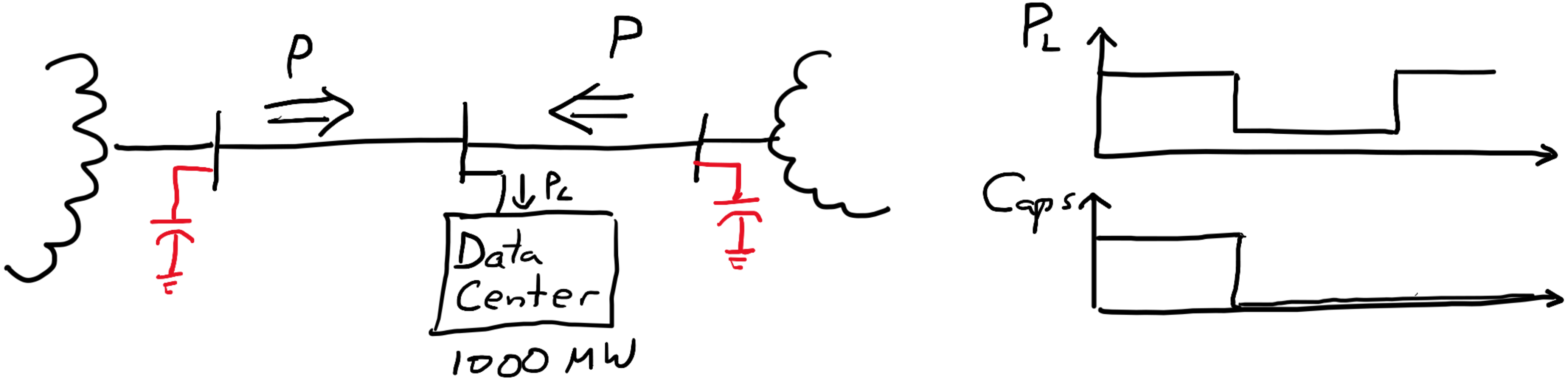


Ride-Through Impact Studies

- Need to ensure that bulk regional disconnection and reconnection (or not) of load will not:
  - Cause load-rejection temporary overvoltage
    - Results in IBR or STATCOM tripping
  - Cause problems with VAR adequacy or dynamic voltage problems
  - Adversely impact frequency of the grid
  - Impact generator resource commitment or create dispatching problems.
  - Study tools may be a mix of Phasor Domain and EMT
- **Special data required:**
  - Ride-through characteristics of the load
  - Ride-through characteristics of nearby devices in the system

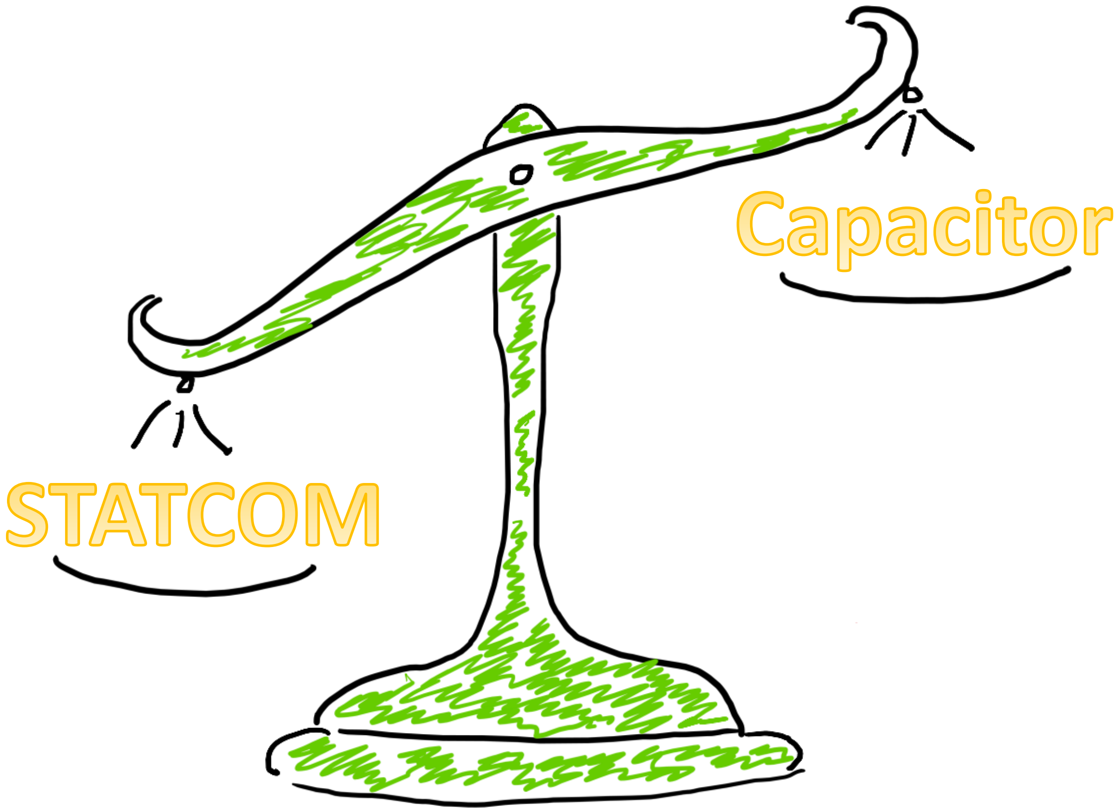
Thinking about dynamic VARs!

- Steady state voltage studies (powerflow) are usually used to determine VAR requirements. Shunt caps are the preferred option to regulate load transfers because they are cheap, and traditionally load doesn't move too fast. Dynamic VARs are often used for load when voltage recovery is problematic (eg. induction motor loads). But…



What is the problem with switched Caps?

1. Caps can be switched off, but not immediately switched on (without special designs). Large, fast load changes will drive large, fast voltage changes!
2. Switching caps causes transients on the system, and wear and tear on breakers.
3. Caps weaken the power system by increasing effective 60 Hz impedance.
4. Caps increase the likelihood of problematic harmonic resonances in the system.
5. **STATCOM solves all of the above, but requires money and time!**

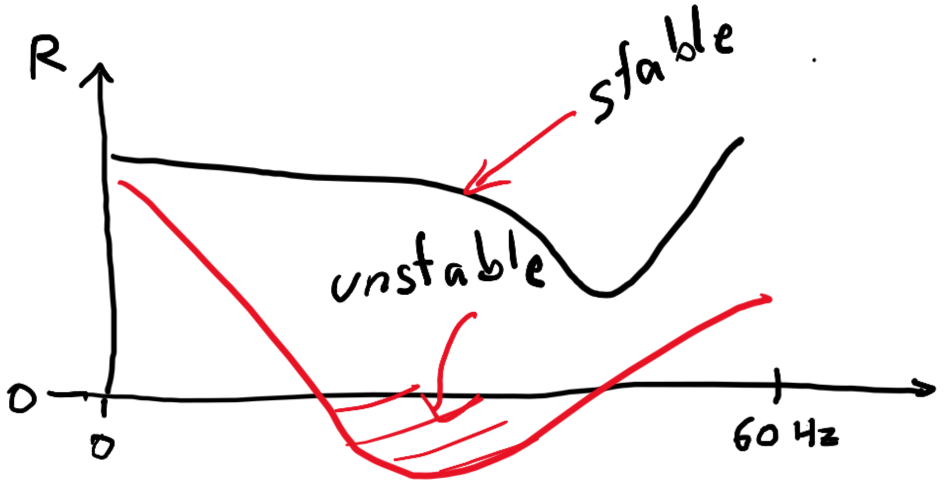


Passive Damping Studies

- SSCI and SSTI are well known phenomena whereby power electronic controls add to or remove damping from the grid.
- If damping becomes negative at an electrical resonance point (eg. Series caps) or at a mechanical resonance point (eg. Machine torsional), instability can occur.
- Study is performed in EMT using very detailed models

Special data required:

- Dynamic impedance characteristics of the load
- Dynamic model of the rest of the grid



What kind of models do you need?

- As always, it depends on what kind of study you’re doing…
- You need to collect the appropriate models for the type of concern you are evaluating!

EMT model ≠ EMT model

PDT model ≠ PDT model

Draft study/model matrix…

Concern	EMT Model with protection (OEM specific)	EMT Model including switching circuitry (OEM specific)	EMT Model including grid-facing control representation (OEM specific)	EMT Model with software cycling (OEM agnostic)	OEM Specific Harmonic Model (Norton Source)	Powerflow Model	PDT Model with software cycling	PDT Model without software cycling
SSTI screening (eg. UIF)	No	No	No	No	No	Yes	No	No
SSTI due to software cycling	No	No	No	Yes	No	No	No	No
Torque impact due to fast changes in load	No	No	No	Maybe	No	Maybe	Maybe	No
SSTI due to control damping	No	No	Yes	No	No	No	No	No
SSCI due to control damping	No	No	Yes	No	No	No	No	No
Harmonic model creation	No	Yes*	Yes*	No	No	No	No	No
Harmonic evaluation	Maybe	Maybe	Maybe	Maybe	Yes	No	No	No
Flicker evaluation	No	No	No	Maybe	No	Yes	No	No
Ride-through sensitivity	Yes*	No	Yes*	No	No	No	No	No
Ride-through impact	Maybe	No	Maybe	No	No	No	No	Maybe
Frequency impact	Maybe	No	No	No	No	No	No	Maybe
IBR/FACTS interaction impact	Maybe	No	Maybe	Maybe	No	Maybe	Maybe	Maybe
Machine mode oscillations due to software cycling	No	No	No	Maybe	No	No	Yes	No
Interarea oscillations	No	No	No	No	No	No	Yes	No
Resource balancing due to ramping	No	No	No	No	No	Yes	No	No
Steady state constraints	No	No	No	No	No	Yes	No	No
Dynamic VAR margin	No	No	No	No	No	Yes	No	Yes
**Alternative to EMT modeling could be detailed laboratory testing on OEM specific equipment*								

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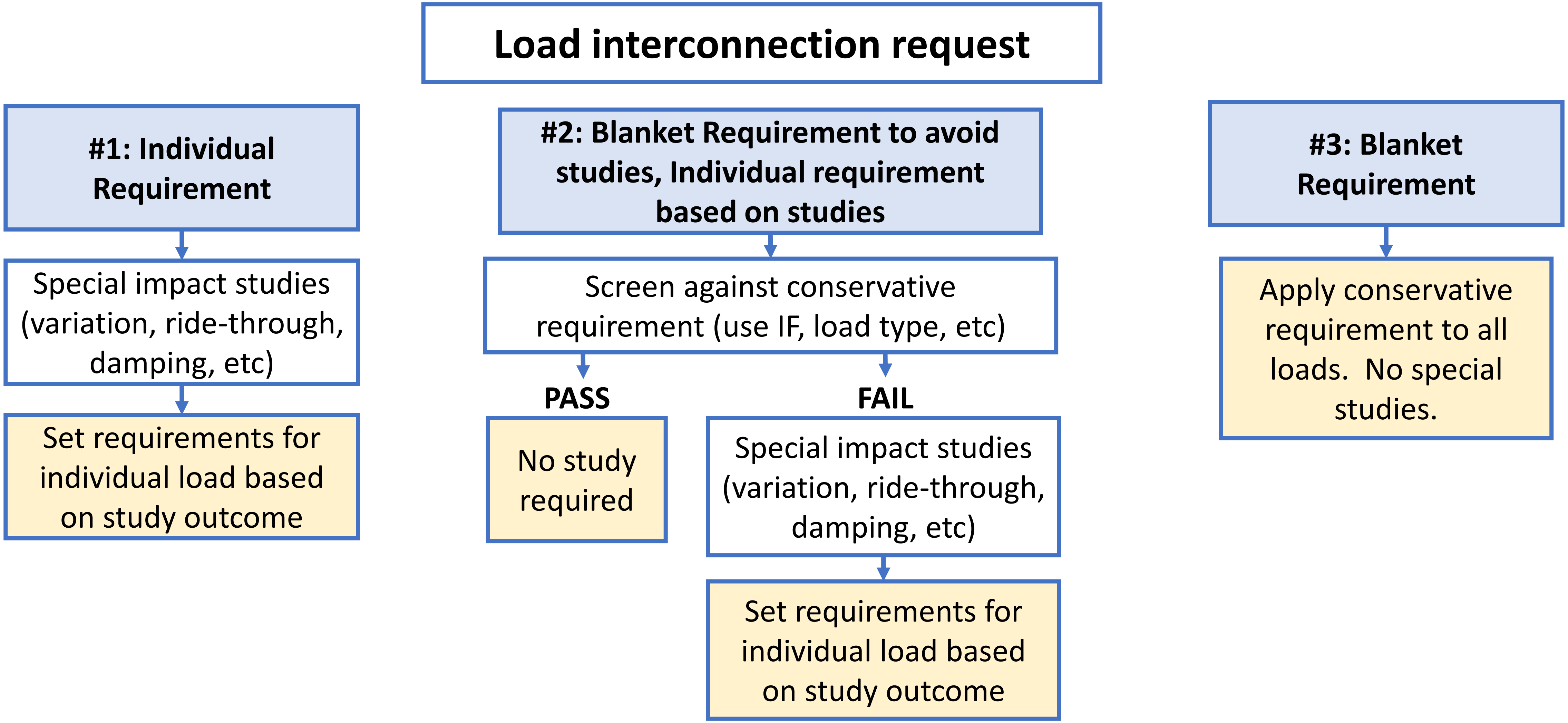
Competing Philosophies for Requirements:



Load interconnection request

#1: Individual Requirement

Special impact studies (variation, ride-through, damping, etc)

Set requirements for individual load based on study outcome

#2: Blanket Requirement to avoid studies, Individual requirement based on studies

Screen against conservative requirement (use IF, load type, etc)

PASS

No study required

FAIL

Special impact studies (variation, ride-through, damping, etc)

Set requirements for individual load based on study outcome

#3: Blanket Requirement

Apply conservative requirement to all loads. No special studies.

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Requirement Philosophy Pros and Cons:

#1: Individual Requirement

Pros:
- Maximum load flexibility

Cons:
- Very heavy study burden
- Re-study may be needed if grid or load changes
- You may find yourself with zero margin

#2: Blanket Requirement to avoid studies, Individual requirement based on studies

Pros:
- Expedited time frames for remote projects over alternative #1

Cons:
- Study burden still heavy
- Re-evaluation may be needed if grid or load changes
- Possibility to miss issues depending on screening approach
- You may find yourself with zero margin again

#3: Blanket Requirement

Pros:
- No study required.
- Accommodates future changes to the grid

Cons:
- Possibility to over-constrain loads, which costs money and may make theoretically good projects unfeasible.
- Possibility to miss issues if requirements are set incorrectly

Framework alternatives – Active Power Variation

1. Limit harmonic/sub-harmonic content in load active power.

   Pros:

   - Can target frequency ranges and limit magnitudes according to equipment limits
   - Allows varied load profiles provided key frequencies aren’t introduced

   Cons:

   - Requires very careful specification of frequency content measurement
   - Requires understanding of how frequencies interplay with each other
   - Requires understanding of how duration of perturbations interacts with magnitude of perturbations.
   - May be more difficult to monitor and enforce, and more difficult to conceptualize.
   - Data center loads may not be able to avoid certain frequencies.

Framework alternatives – Active Power Variation

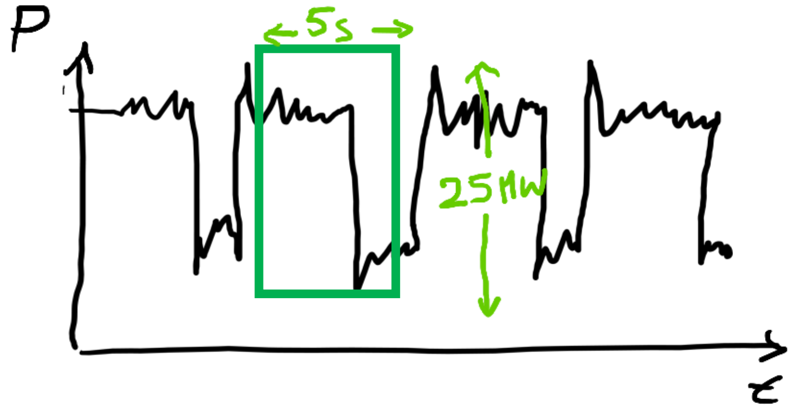
2. Limit absolute variation magnitude.

Pros:

- Conceptually simple to understand
- Addresses multiple concerns
- Allows any type of load variation within the magnitude limit.

Cons:

- Hard to choose a single value that protects equipment adequately and doesn't over-constrain load shapes.



Framework considerations – Ride through

- You can use a ride-through profile (similar to IBR FRT curves) but…
  - Does that mean no-trip or no-temporary-reduction (eg. UPS pickup)?
  - If temporary reduction is allowed, how fast should they return? 1s?
    - Note: Consider frequency, load-rejection overvoltage, dynamic voltage control, and how many loads may trip together for a common event.
  - Load rejection of multiple collocated loads could cause significant temporary overvoltage. **How can we fix this?**
- Consider that many or maybe most loads will not be able to initially meet this criteria, particularly if you don’t allow temporary reduction.

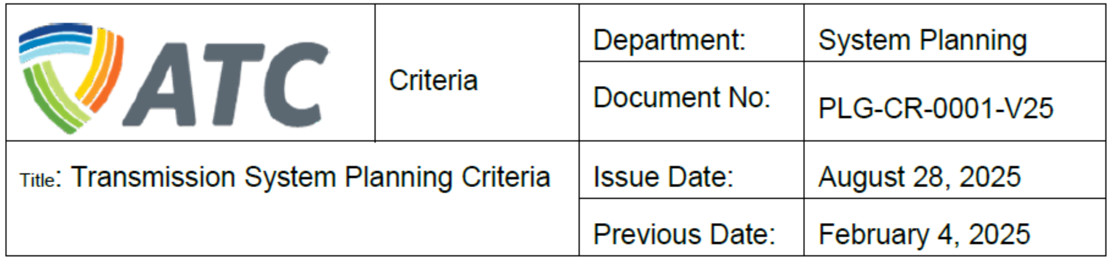
Example requirement: ATC

- Load Interconnection Guide, rev 15 – published August 22, 2025 (pages 32-35)
- ATC Planning Criteria, V25 – published August 28, 2025 (pages 34-37)
- Uses a blanket requirement, but allows studies to prove exceptions.

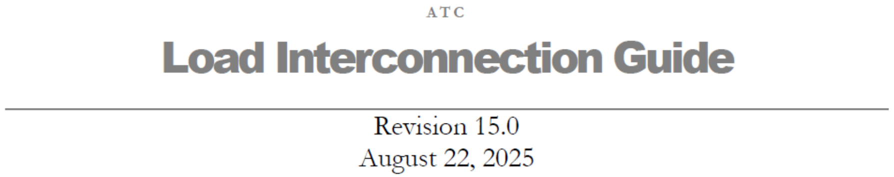
#2: Blanket Requirement to avoid studies, Individual requirement based on studies

- Uses absolute variation magnitude limit:

  <25 MW over any 5 second period



ATC	Criteria	Department:	System Planning
		Document No:	PLG-CR-0001-V25
Title: Transmission System Planning Criteria		Issue Date:	August 28, 2025
		Previous Date:	February 4, 2025

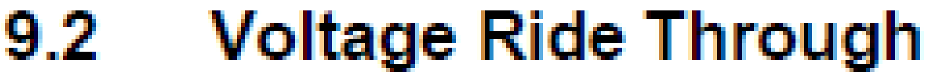


ATC

Load Interconnection Guide

Revision 15.0
August 22, 2025

Example Criteria: ATC (Loads > 200 MW)



9.2 Voltage Ride Through

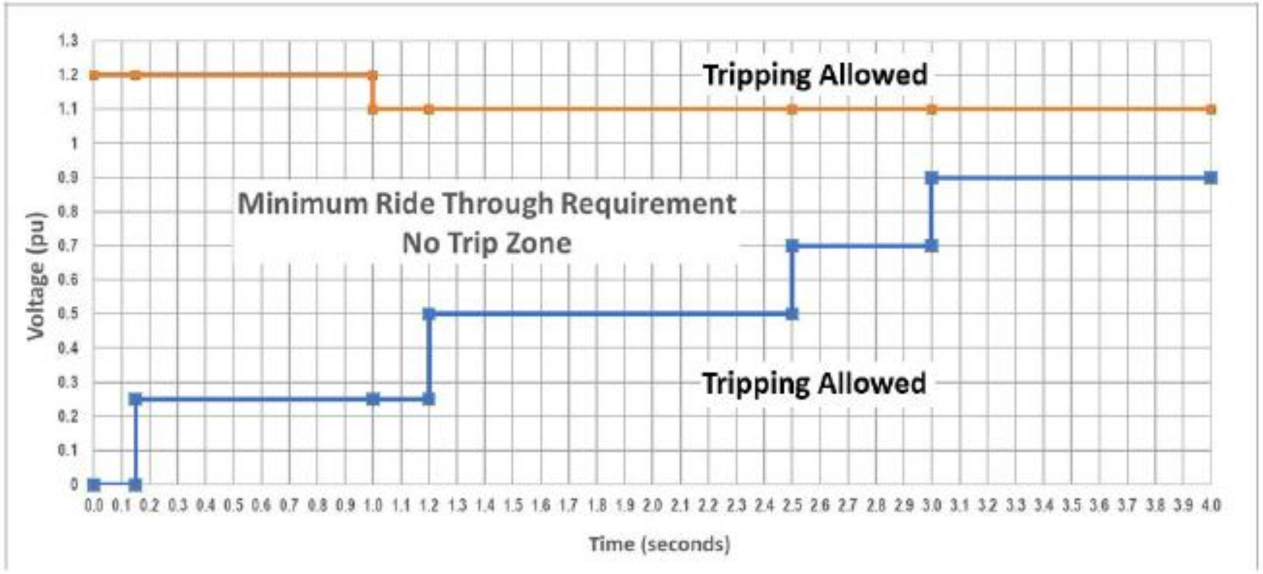
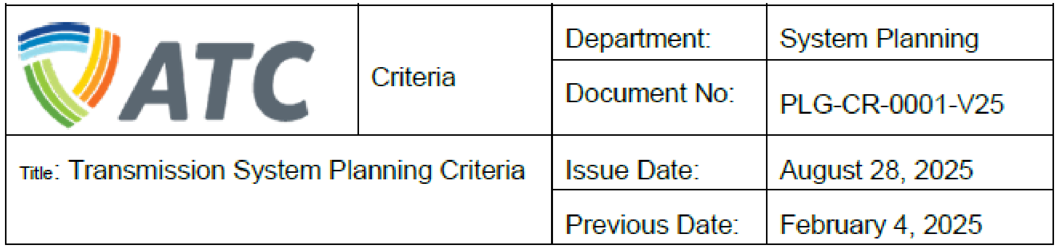


Figure 9.2-1: Voltage Ride Through Curve for Large Loads



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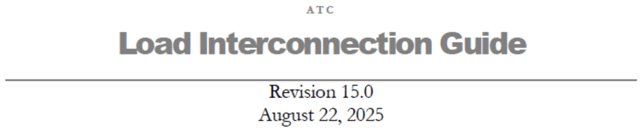

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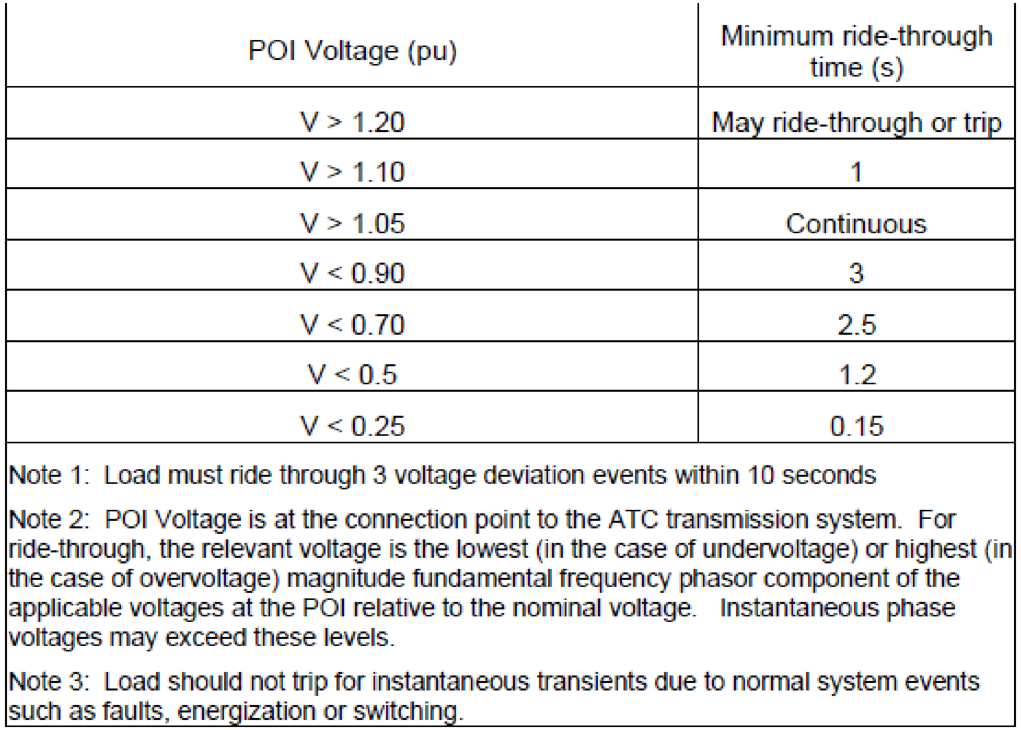


POI Voltage (pu)	Minimum ride-through time (s)
V > 1.20	May ride-through or trip
V > 1.10	1
V > 1.05	Continuous
V < 0.90	3
V < 0.70	2.5
V < 0.5	1.2
V < 0.25	0.15

Note 1: Load must ride through 3 voltage deviation events within 10 seconds

Note 2: POI Voltage is at the connection point to the ATC transmission system. For ride-through, the relevant voltage is the lowest (in the case of undervoltage) or highest (in the case of overvoltage) magnitude fundamental frequency phasor component of the applicable voltages at the POI relative to the nominal voltage. Instantaneous phase voltages may exceed these levels.

Note 3: Load should not trip for instantaneous transients due to normal system events such as faults, energization or switching.

Example Criteria: ATC (Loads > 200 MW)

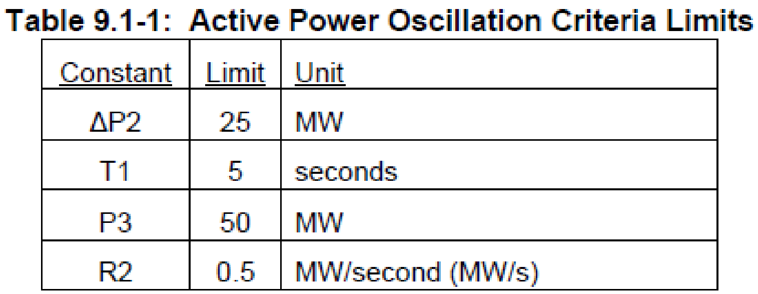
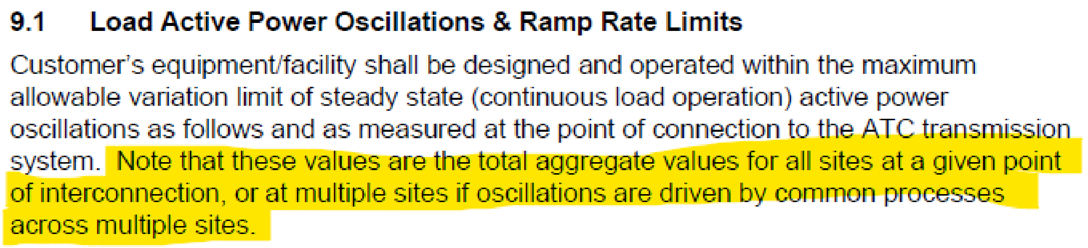


Table 9.1-1: Active Power Oscillation Criteria Limits

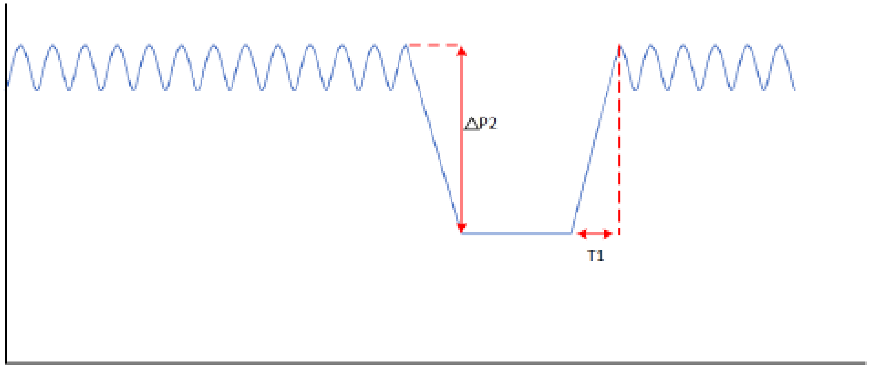
Constant	Limit	Unit
ΔP2	25	MW
T1	5	seconds
P3	50	MW
R2	0.5	MW/second (MW/s)



9.1 Load Active Power Oscillations & Ramp Rate Limits

Customer's equipment/facility shall be designed and operated within the maximum allowable variation limit of steady state (continuous load operation) active power oscillations as follows and as measured at the point of connection to the ATC transmission system. Note that these values are the total aggregate values for all sites at a given point of interconnection, or at multiple sites if oscillations are driven by common processes across multiple sites.

Criterion 1: Repetitive changes in load active power must be <ΔP2 for any period of time <T1 seconds calculated using a sliding time window.



Criterion 2: Any change (increase or decrease) in active power >P3 MW should be limited to <R2 MW/s.

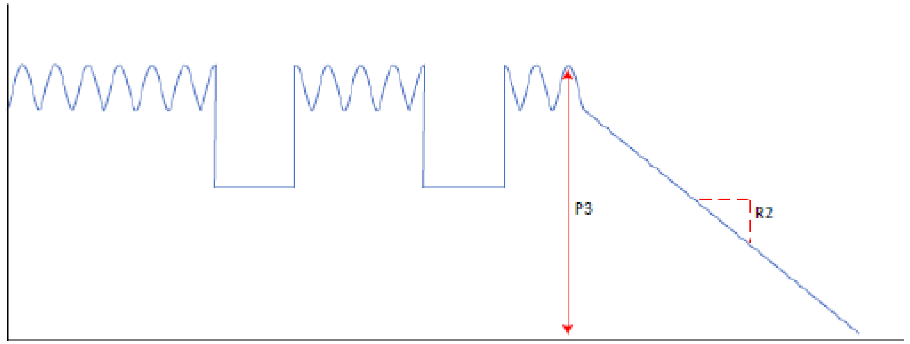


Figure 9.1-4: Active Power Criterion for P3 and R2 Example

Variability Mitigation

- "Load floor"
- HV/MV energy storage
  - E-STATCOM with or without GFM BESS
- DC level (power supply) storage (eg Nvidia GB300 or DC storage)
- Low voltage GFM BESS or GFM BESS behind series reactor (+ load-tracking?)
- Full conversion UPS with large energy storage or supercapacitors
- Thyristor switched resistor
- Software mitigation?

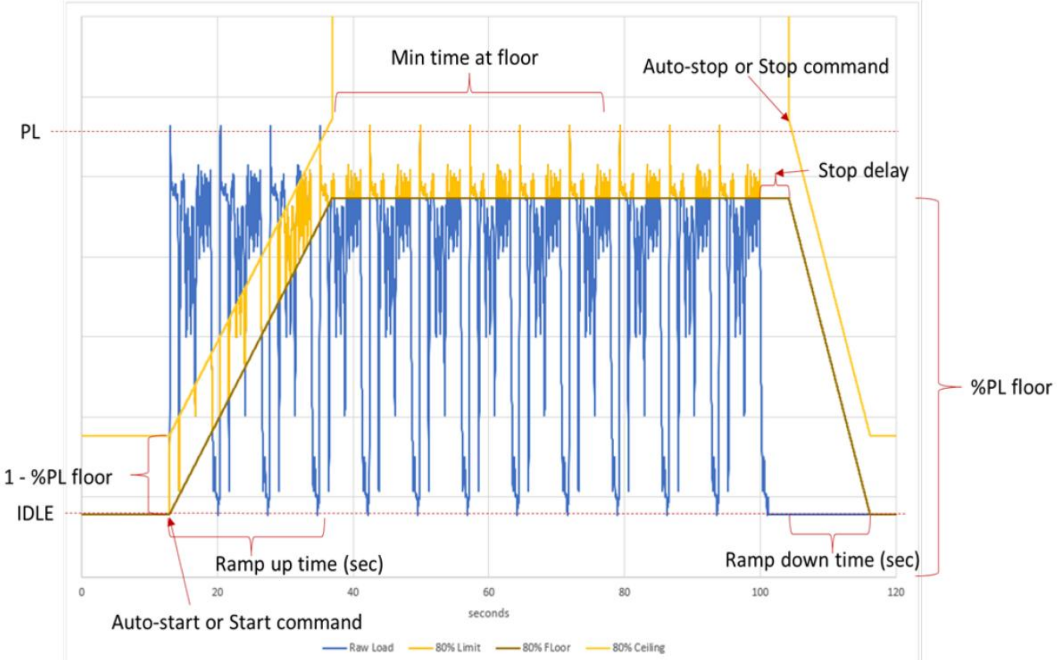
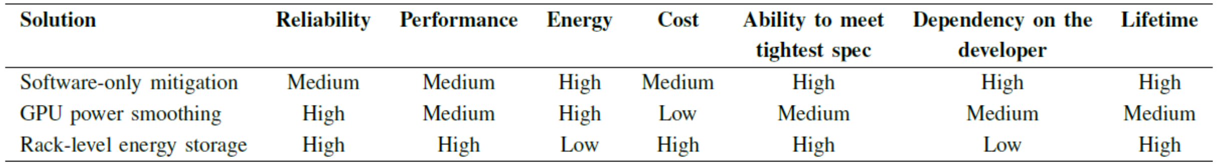


Fig. 7. Energy-storage solution simulated on the power waveform from Figure [1]



Solution	Reliability	Performance	Energy	Cost	Ability to meet tightest spec	Dependency on the developer	Lifetime
Software-only mitigation	Medium	Medium	High	Medium	High	High	High
GPU power smoothing	High	Medium	High	Low	Medium	Medium	Medium
Rack-level energy storage	High	High	Low	High	High	Low	High

TABLE I

SUMMARY OF VARIOUS PROPOSED SOLUTIONS. FOR ENERGY, COST, AND DEPENDENCY ON THE DEVELOPER, LOWER IS BETTER.

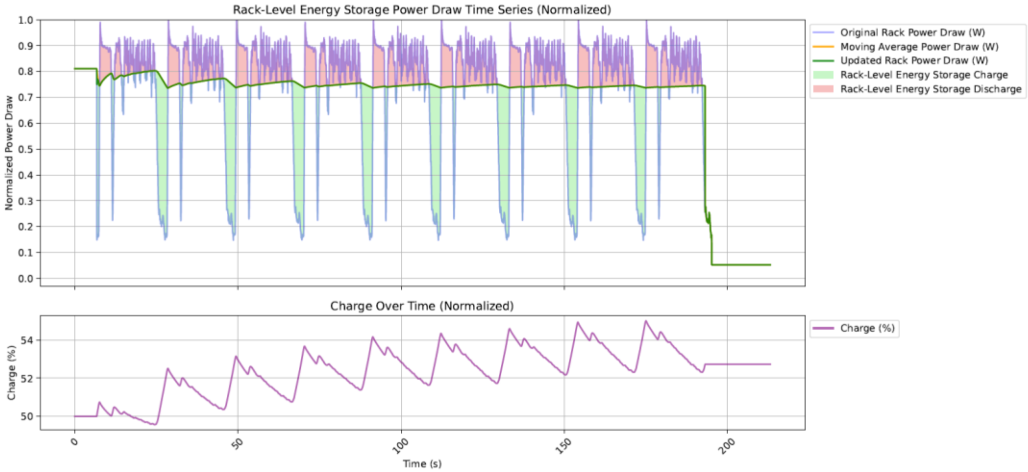


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Fig. 7. Energy-storage solution simulated on the power waveform from Figure [1]