EnerNex

CESI Group

Large Load Integration Challenges and Solutions

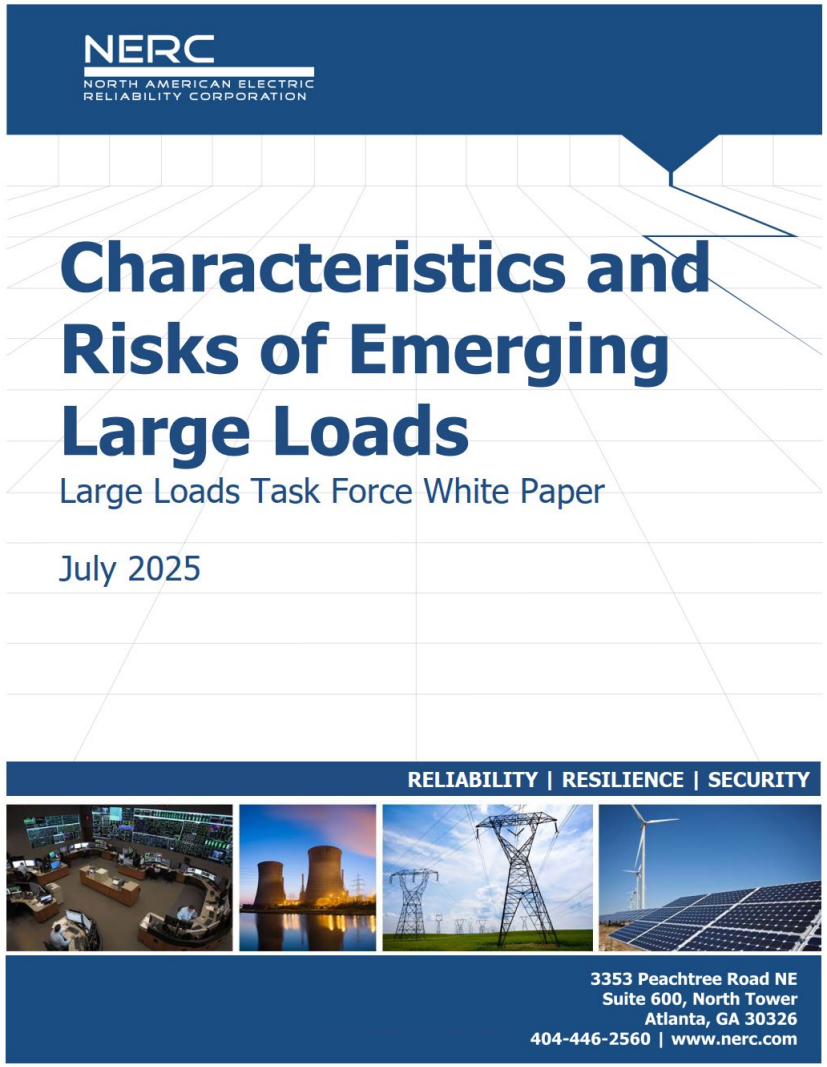
2026 Electromagnetic Transient Simulation Workshop

David Mueller

August 18, 2026

NERC Large Loads Task Force

- Electrical behavior of emerging large loads during both normal AND abnormal grid conditions represents new challenges for planners and operators
- Operating experience with emerging large loads remains limited
- Large loads may come in different forms, but the rapid growth associated with data centers tends to be the focus on the characteristics and potential risks of the Bulk Electric System (BES)

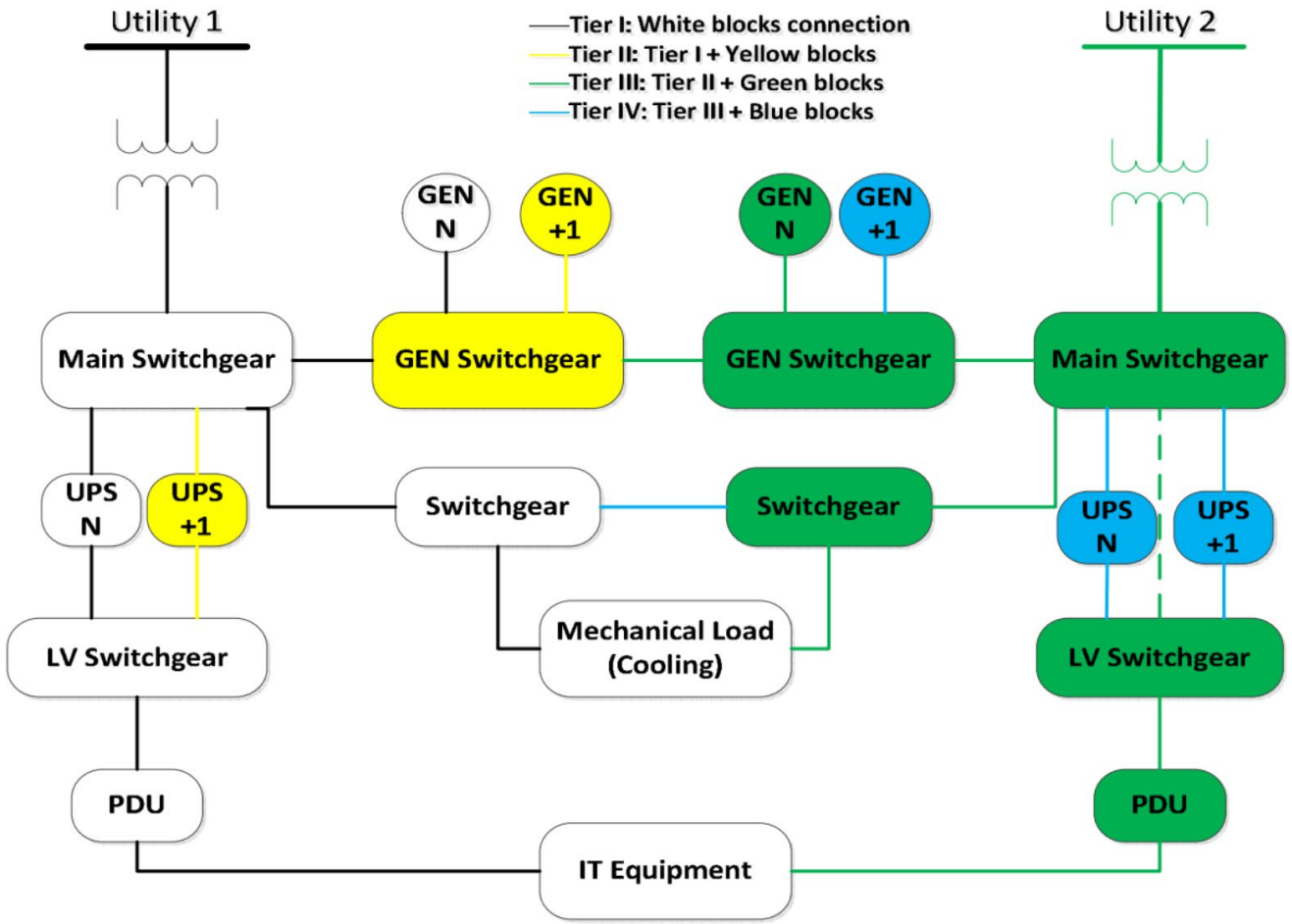


What Are ‘Large Loads'?

NERC LLTF Definition: Any commercial or industrial load facility or aggregation of load facilities at a single site behind one or more point(s) of interconnection that can pose reliability risks to the BPS due to its demand, operational characteristics, or other factors.

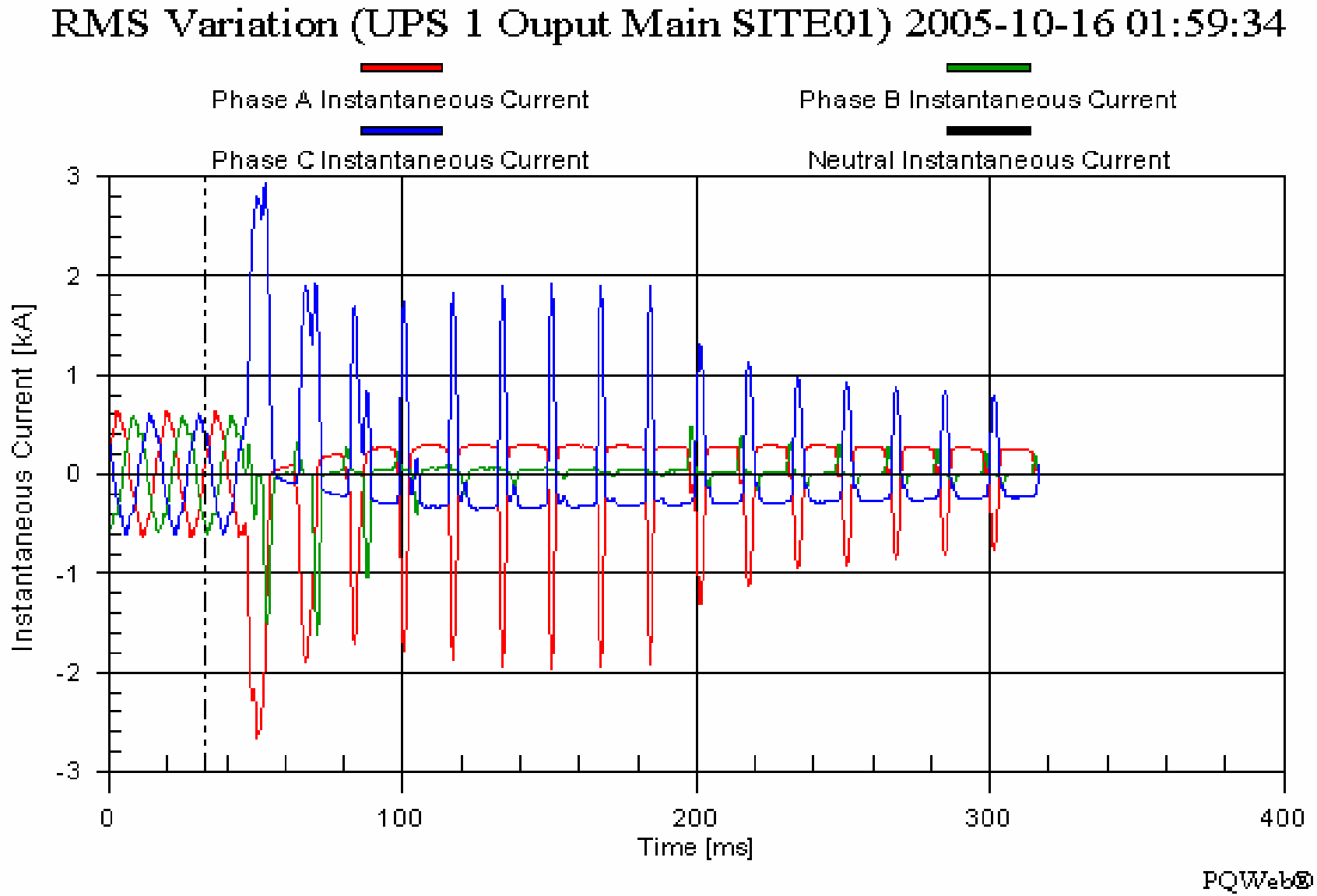
Data Centers & Computational Loads	Industrial Loads	Hydrogen Production Facilities
• AI training & inference facilities • Hyperscale cloud data centers • Cryptocurrency mining operations • Traditional enterprise colocation • High Performance Computing (HPC)	• Electric arc furnaces (EAF) • Steel mills & metal smelters • Semiconductor fabrication plants • Chemical & petrochemical processing • Oil & gas electrification	• Electrolysis-based H_2 production • Multi-GW facilities in development • >85% power electronic converter loads • Electrolyzer arrays (5–10 MW each) • Newest reliability considerations
Fastest growing — AI facilities up to 2 GW planned	***~20% of forecasted growth; historically well-studied***	***Newest category; heavy power electronics concentration***

High Reliability Data Center Design



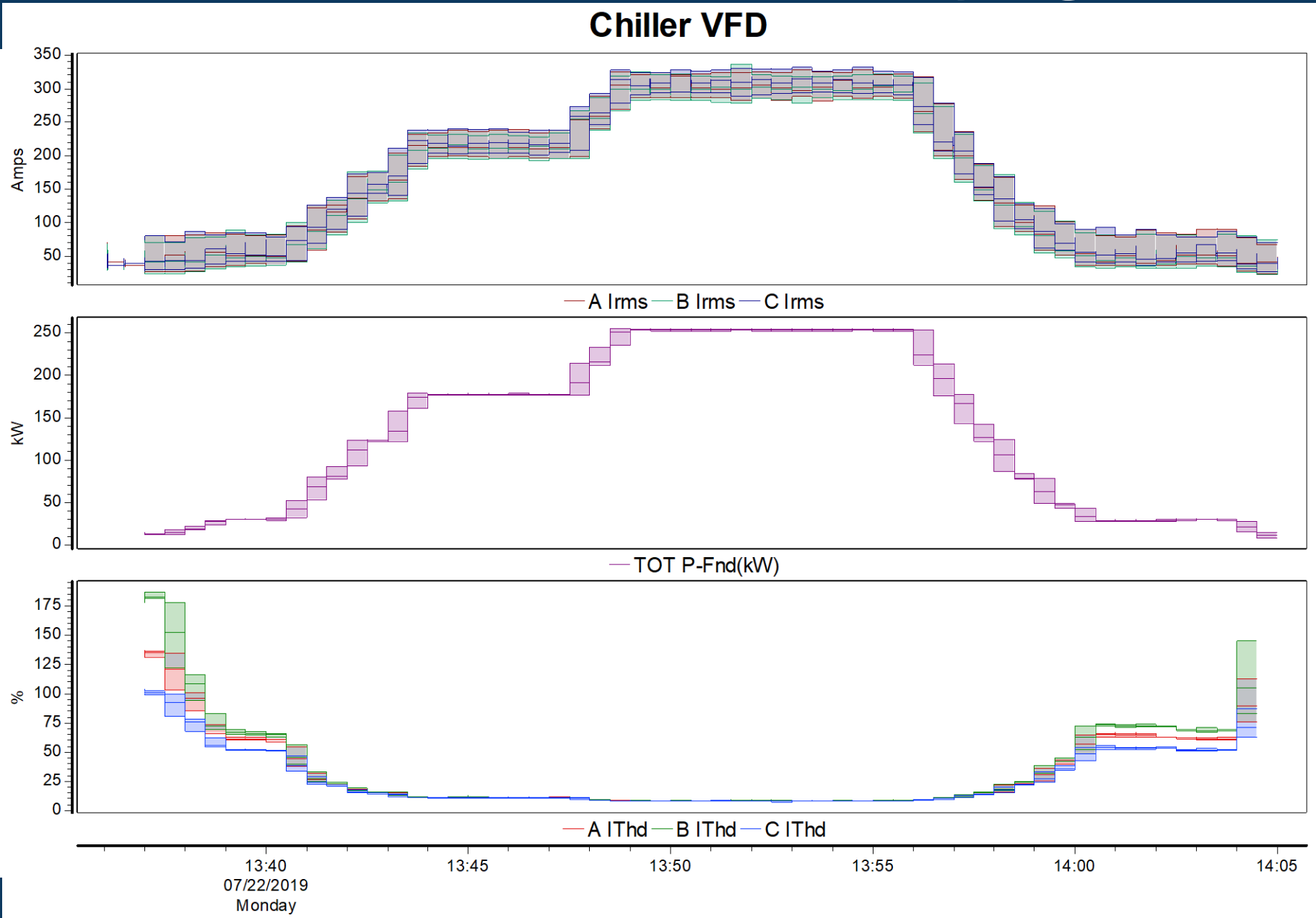
Source: NERC Large Loads Task Force

UPS Current – Bypass Assist

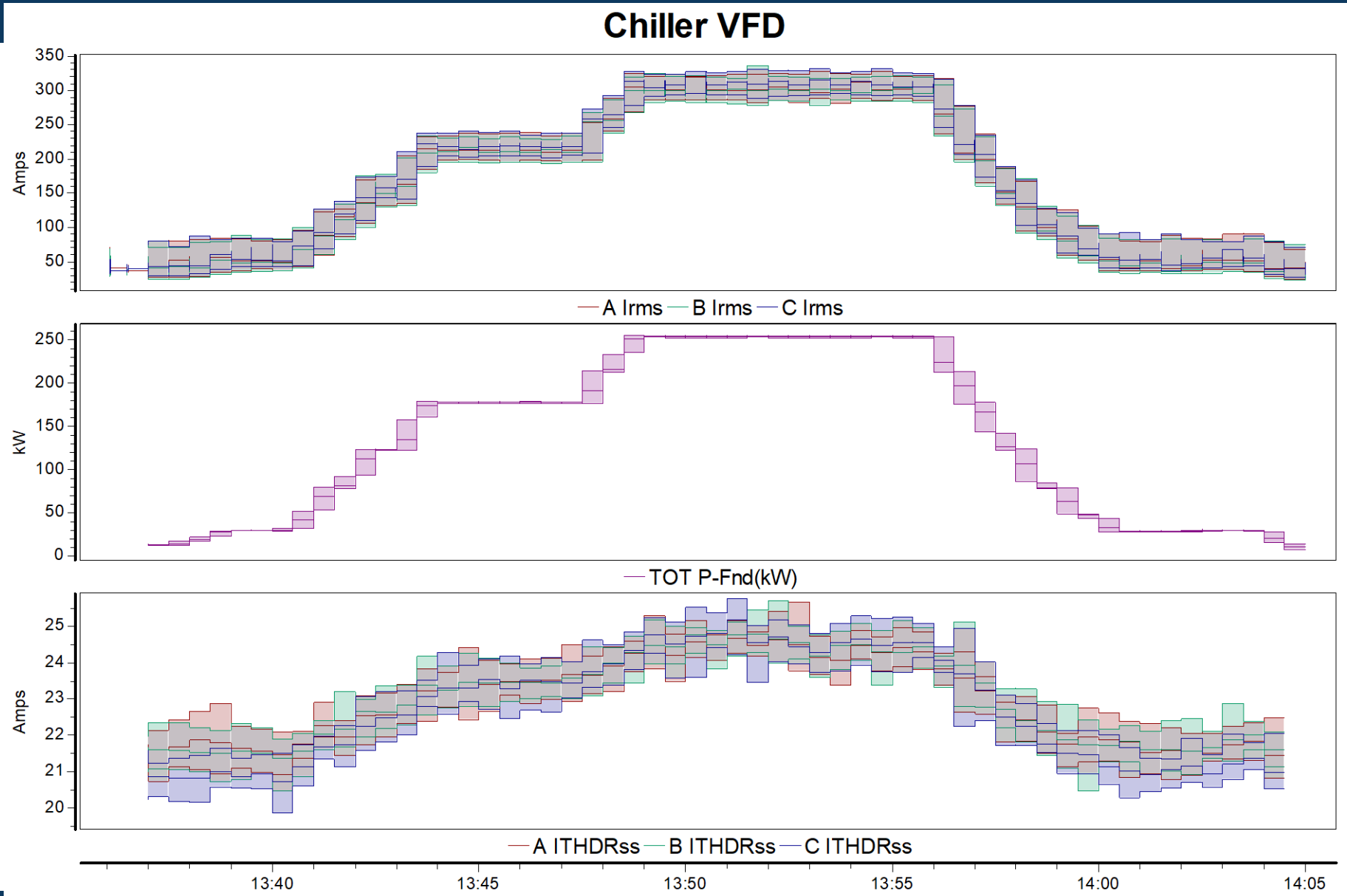


Controlling Harmonics

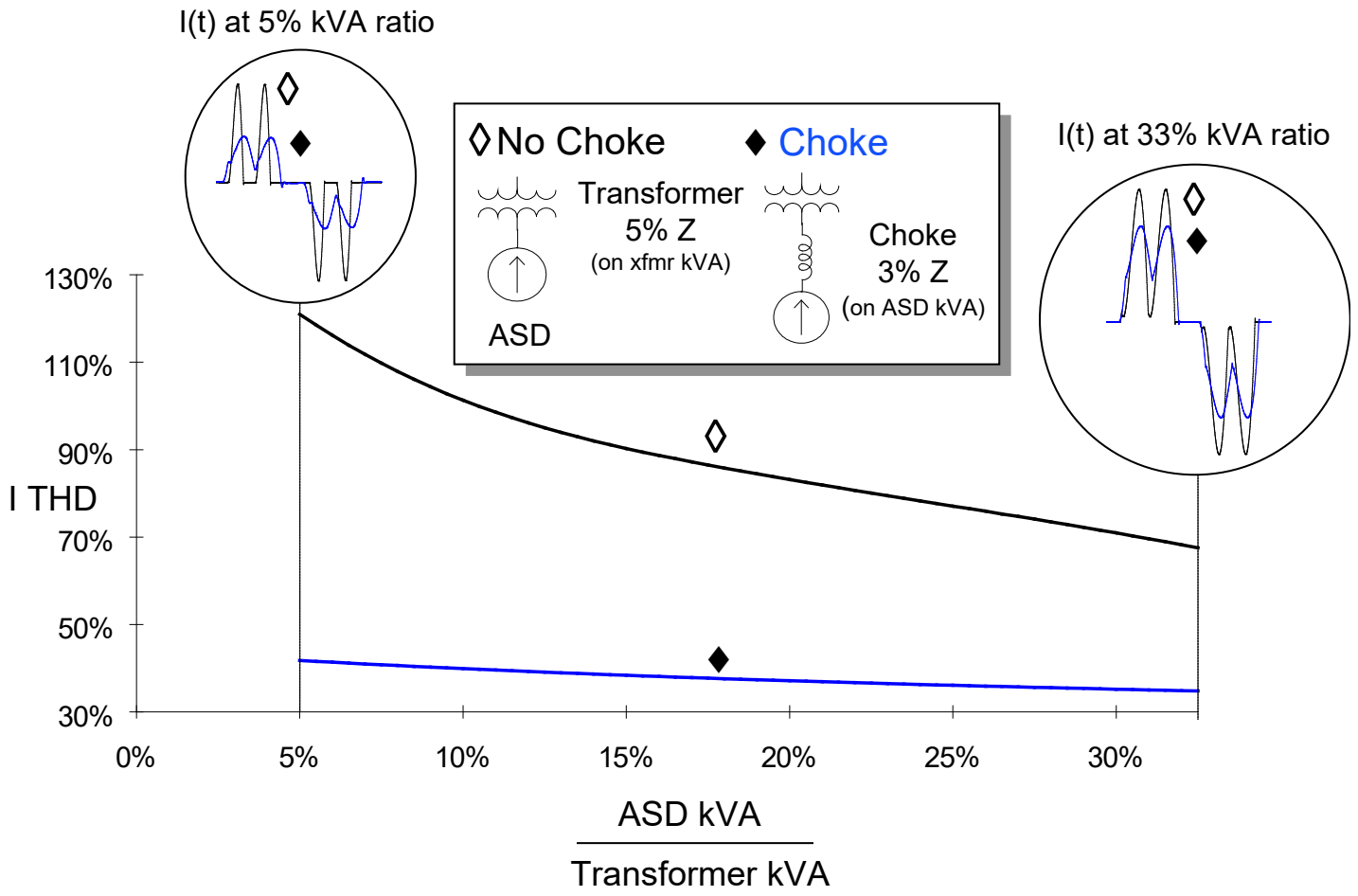
Chiller VFD Harmonics Under Varying Load



Chiller VFD Harmonic Current with Varying Load

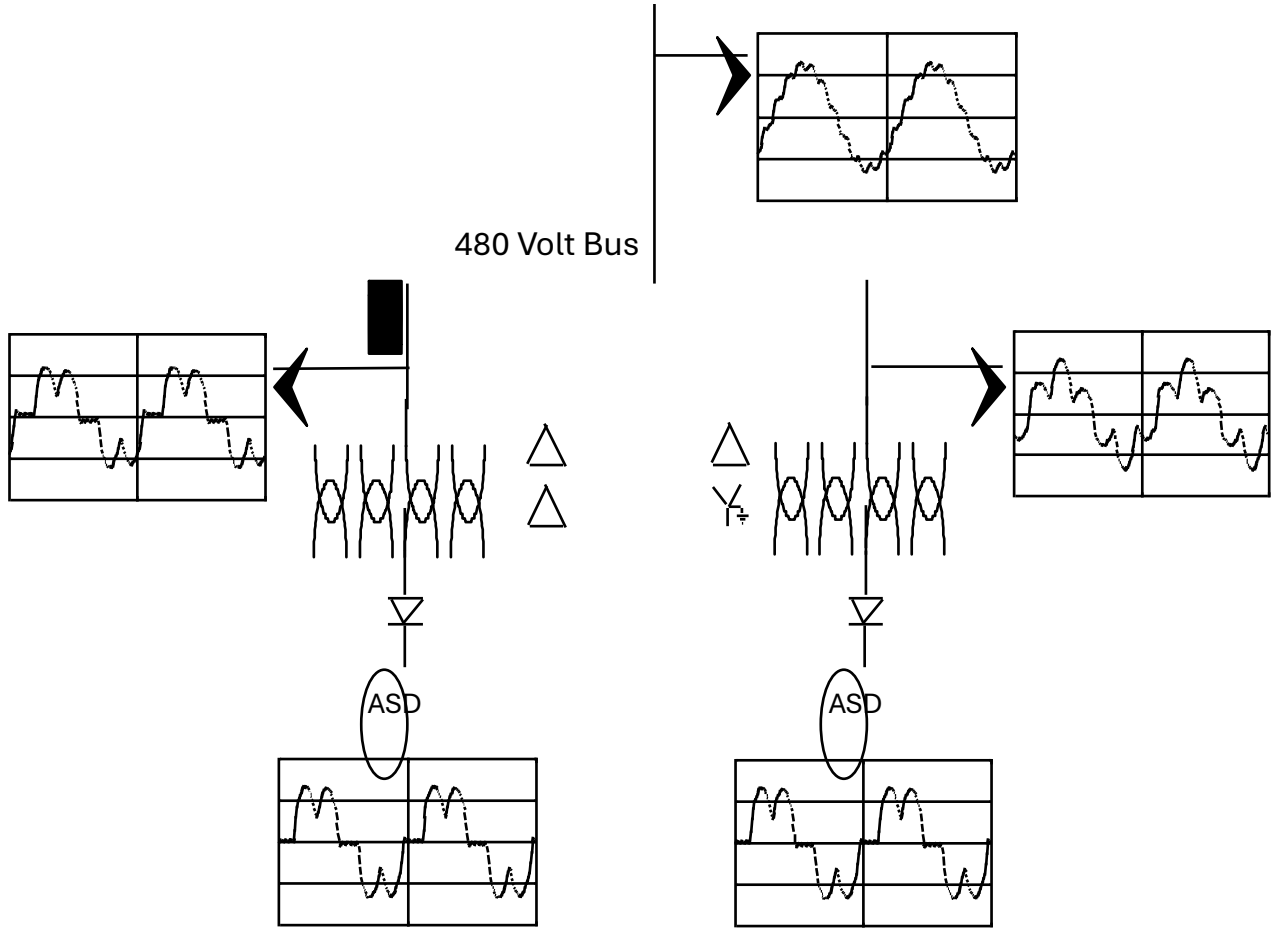


Effect of ac Line Choke on an ASD



12 Pulse Cancellation

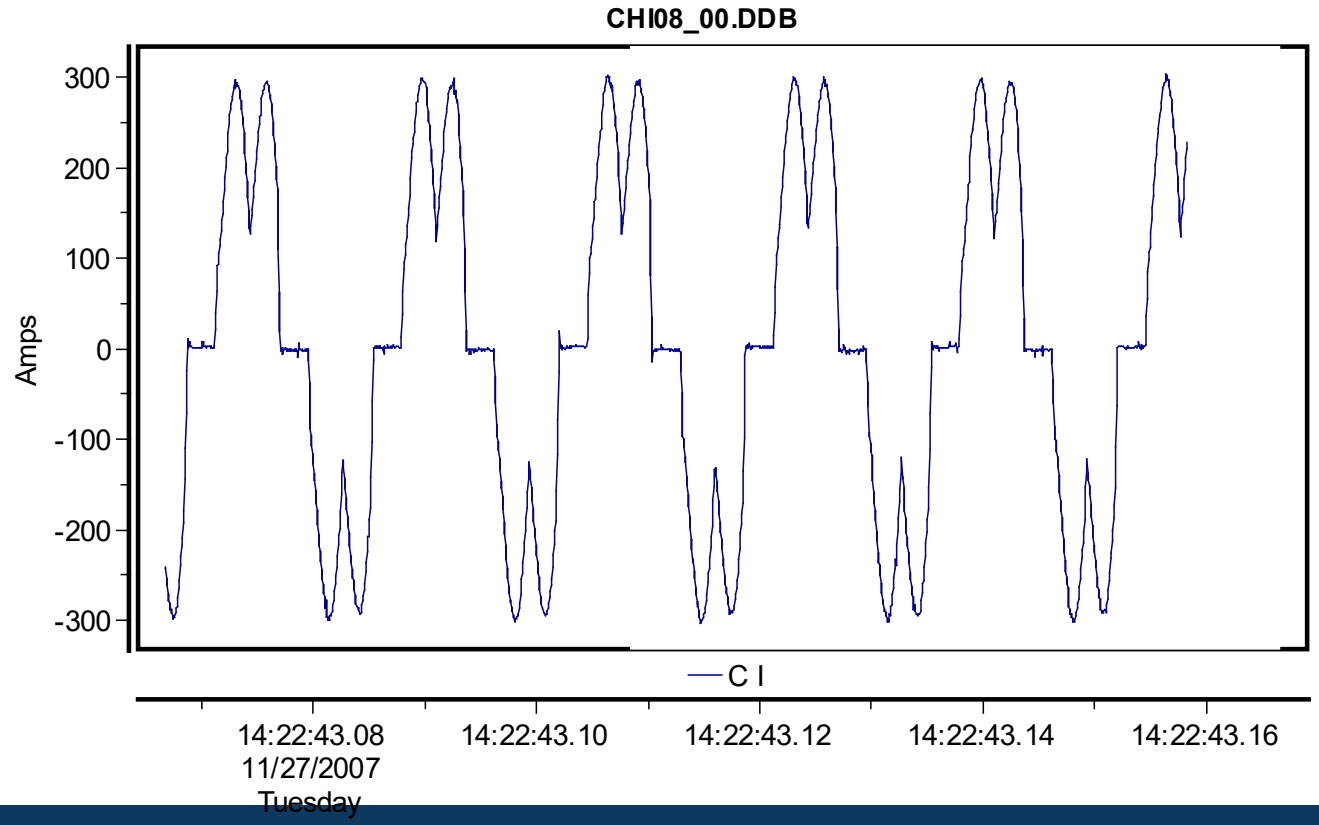
60% of the plant load could be ASDs without exceeding 519 guidelines if they are in a 12 pulse configuration



Mechanical Load Harmonics? Chiller Line Current

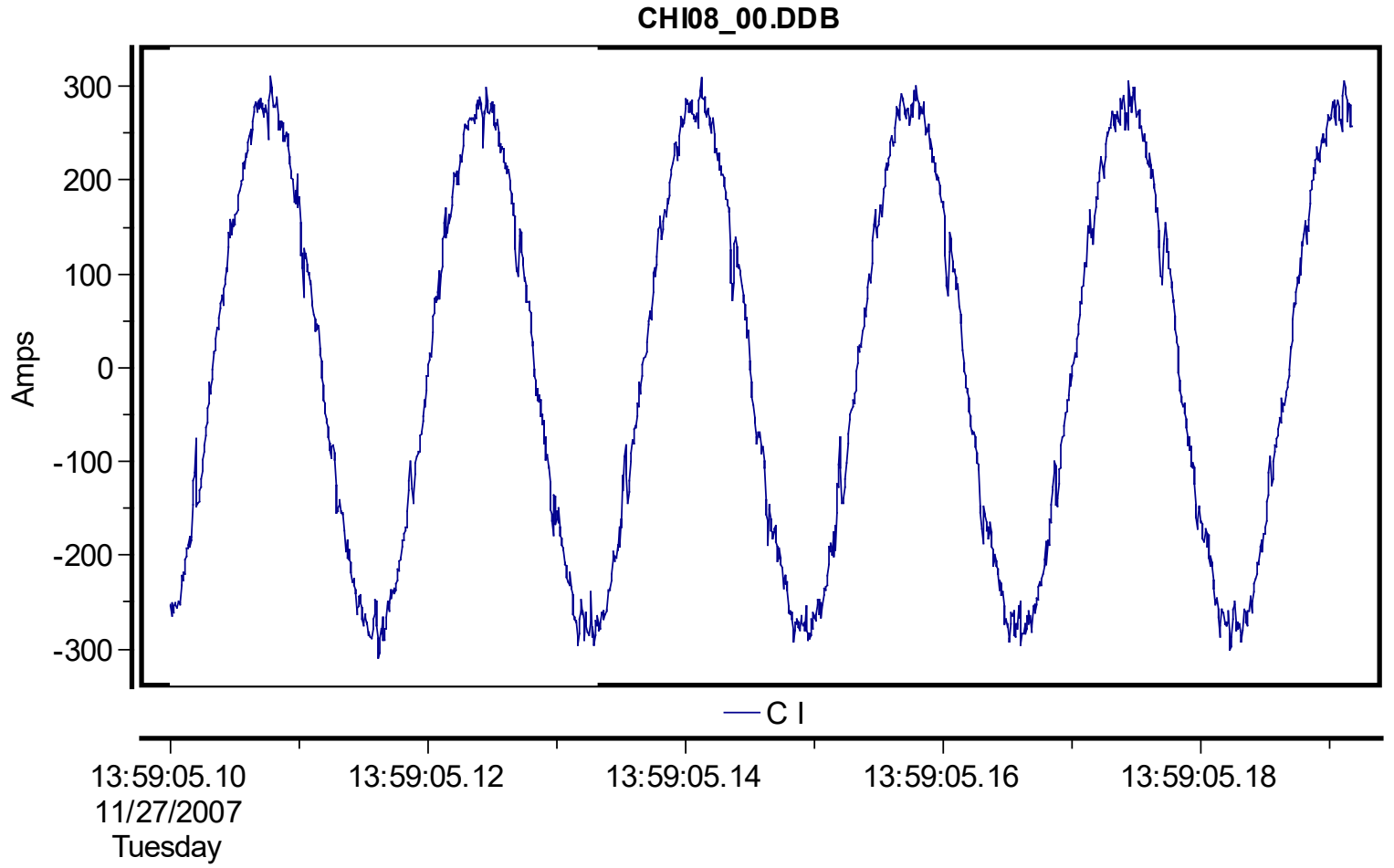
- Current (Unfiltered)

Current (Ithd=38%)



Chiller Current (with Active Filter)

(Ithd=7.5%)



Filters for Variable Frequency Drive Units

Matrix® AP Technical Reference Manual 208V – 690V

MTE POWER QUALITY SOLVED

Basic Schematic Diagram

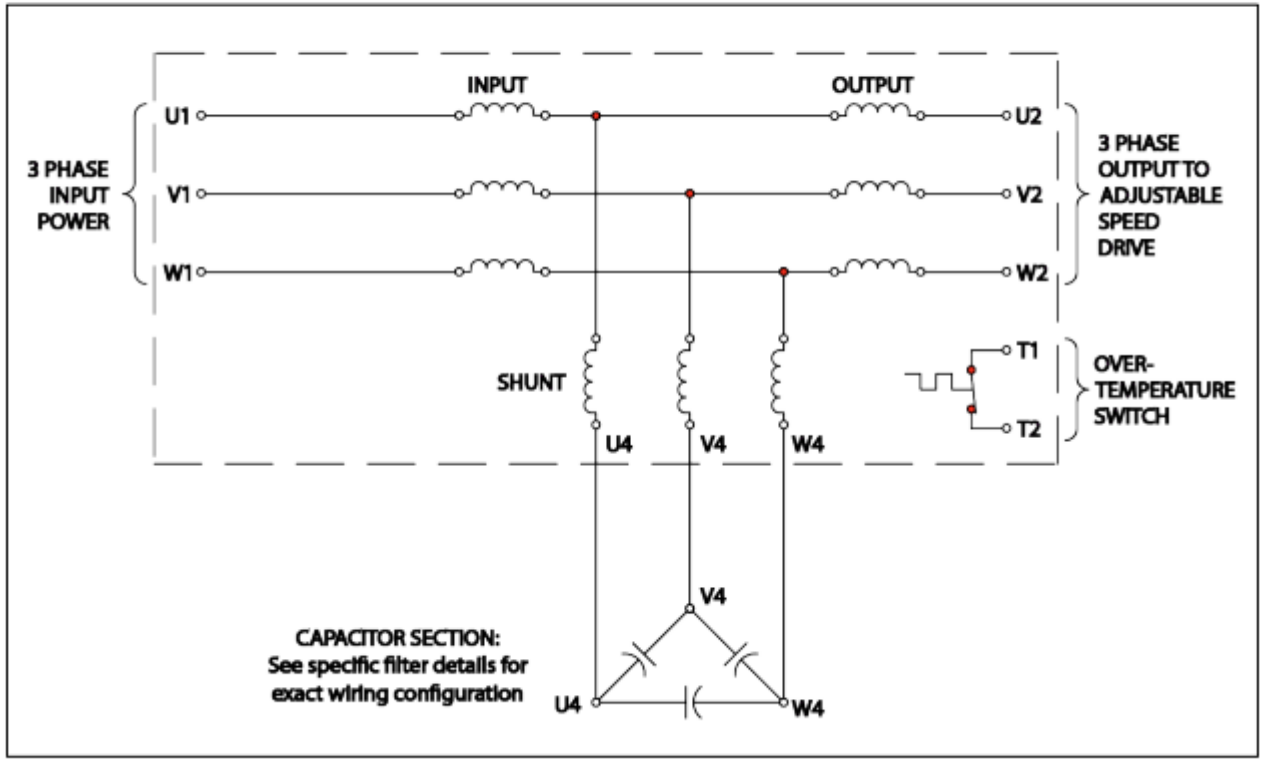
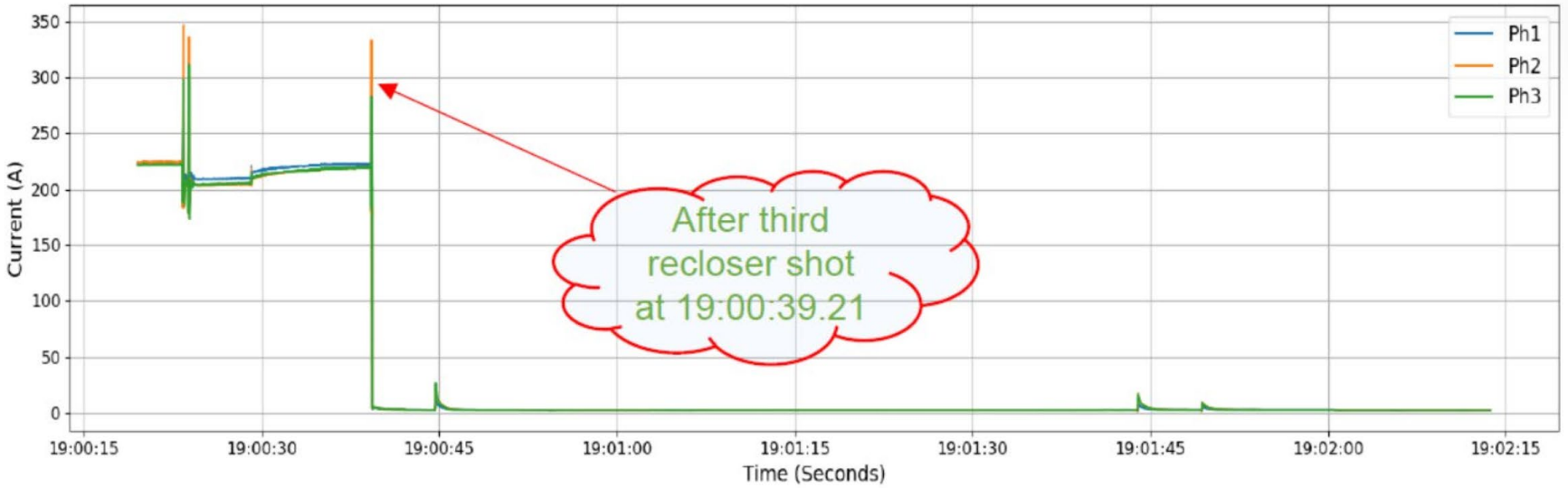


Figure 5-1: Basic Schematic Diagram

Low Voltage Ride Through (LVRT) Concerns

Stability Risks: Ride-Through

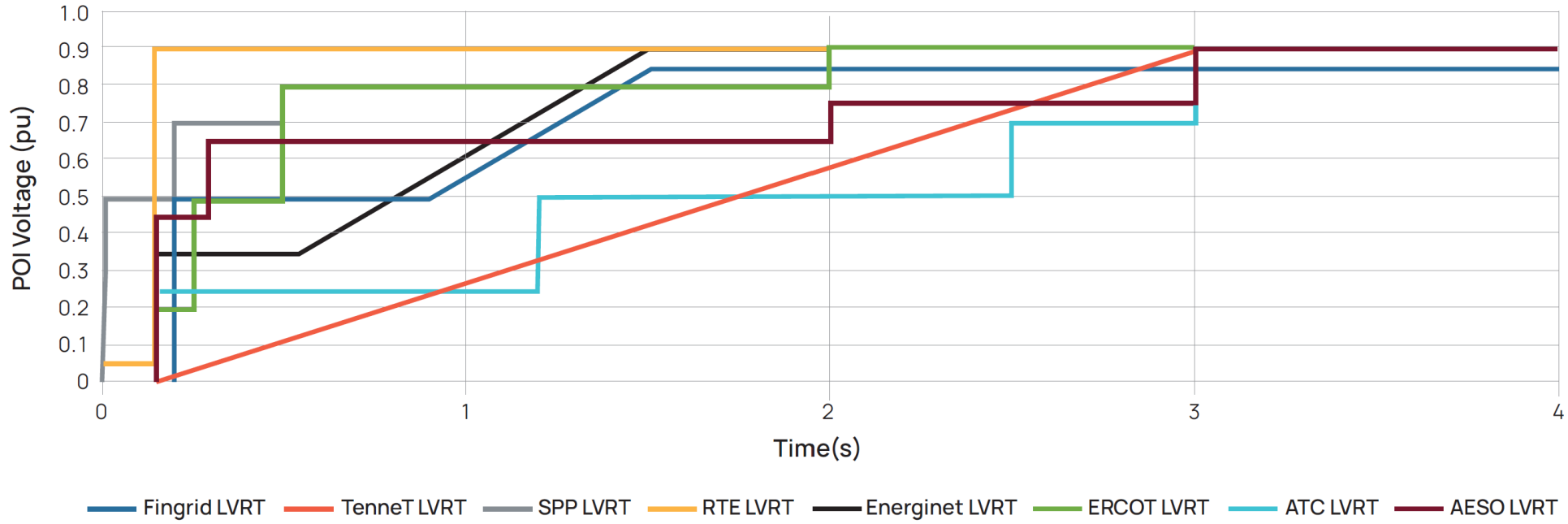
- Large loads transfer to standby backup systems
- Some data centers can switch to backup power after 3 transient voltage disturbances within 1 minute (observed in EI load-transfer event)
- July 10, 2024 Eastern Interconnect event: Lightning arrestor failure on 230 kV line → multiple faults in 82 seconds → Voltage depressions 0.25–0.40 p.u. → 1,500 MW of load lost via customer-side protection (not utility trip) → frequency rose to 60.053 Hz



Source: NERC LLTF

Low Voltage Ride Through (LVRT)

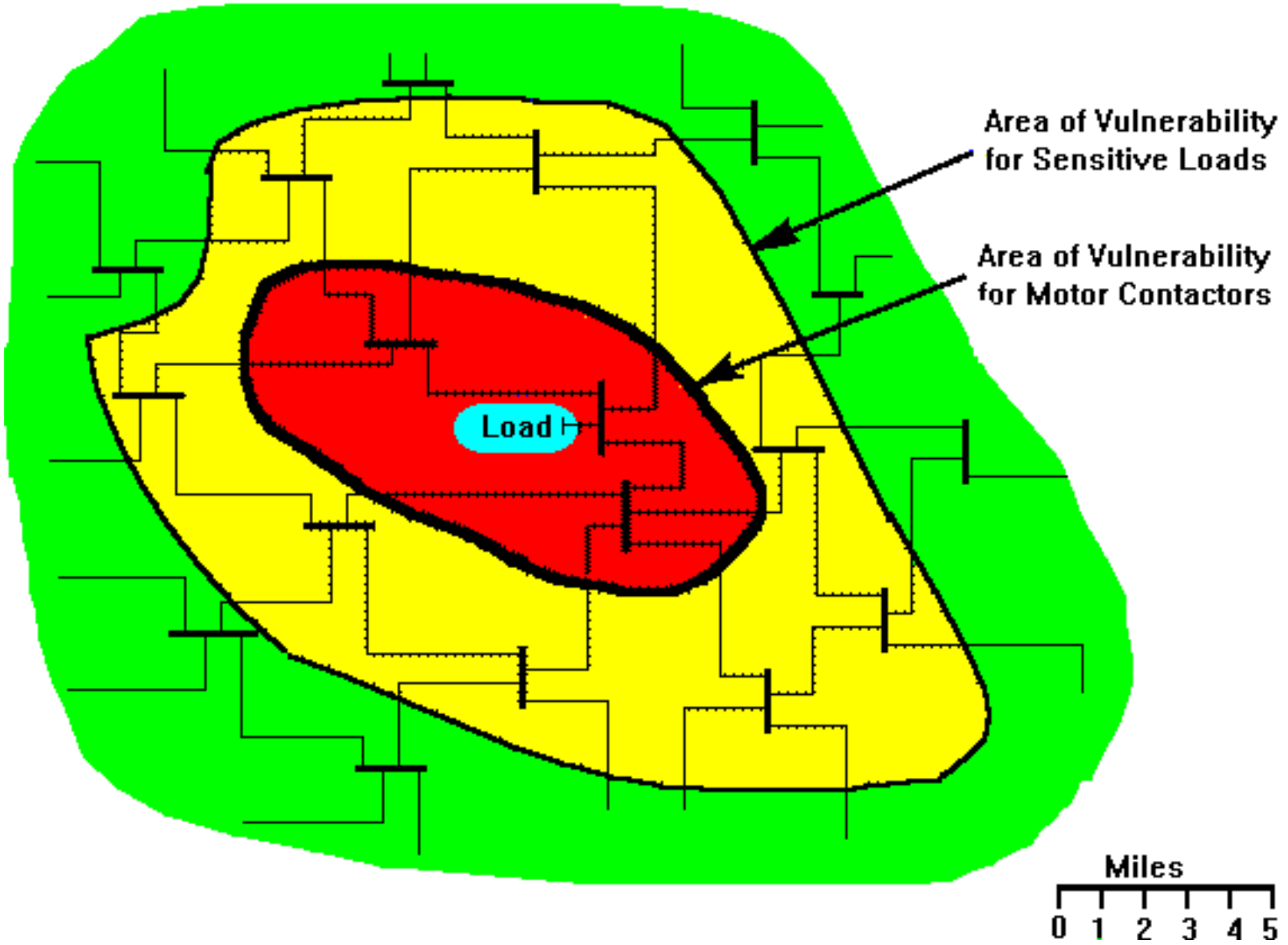
Comparison of Voltage Ride-Through Requirements: Low VRT Profiles



Notes: AESO = Alberta Electric System Operator; ATC = American Transmission Company; ERCOT = Electric Reliability Council of Texas; LVRT = Low-voltage ride-through; RTE = Le Résea de Transport d'Electricité; SPP = Southwest Power Pool.

Source: "Large Load Performance Requirements – Current Practices and Recommendations"
Electrical Systems Integration Group (ESIG) February 2026

Fault Location Area of Vulnerability



AI Training Load Fluctuations

Subsynchronous Oscillations (Forced)

Power Variations of AI Loads

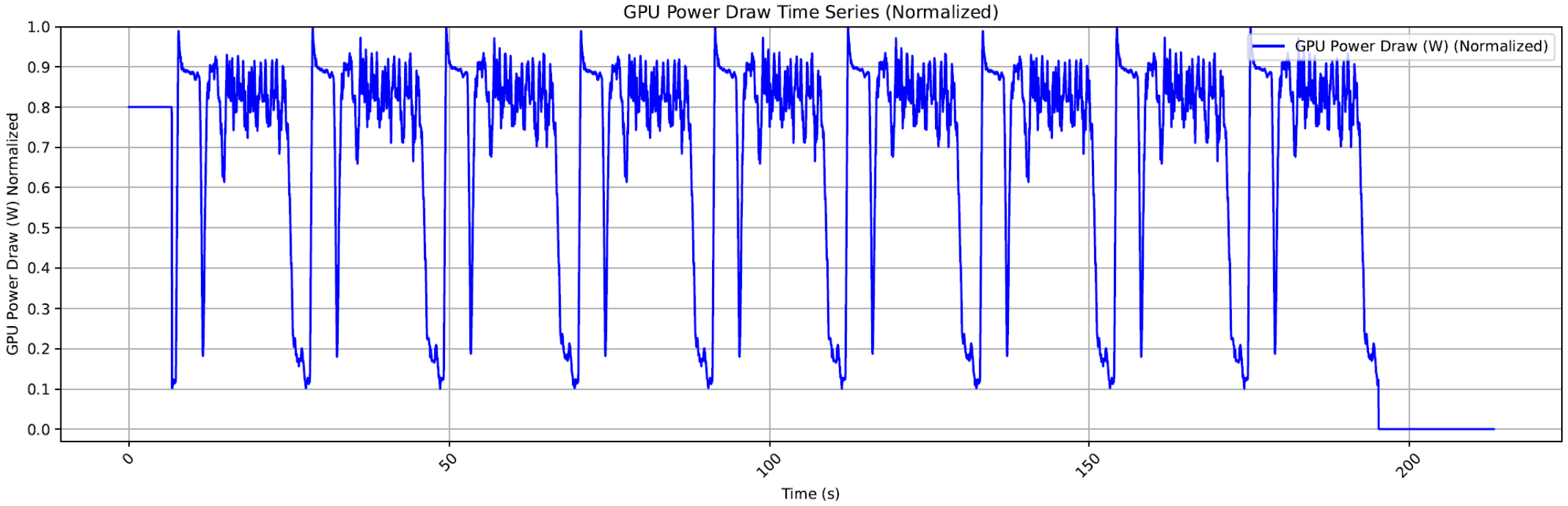


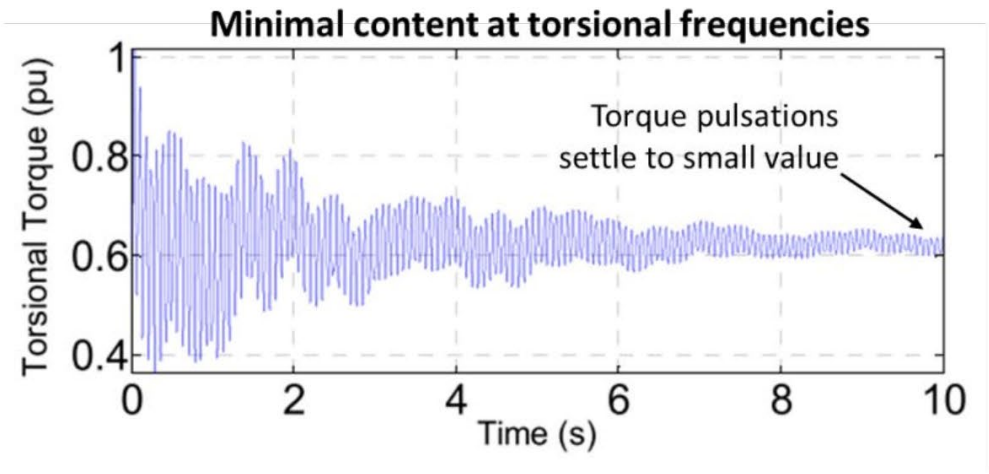
Fig. 1. Power readings from an at-scale training job on DGX-H100 racks.

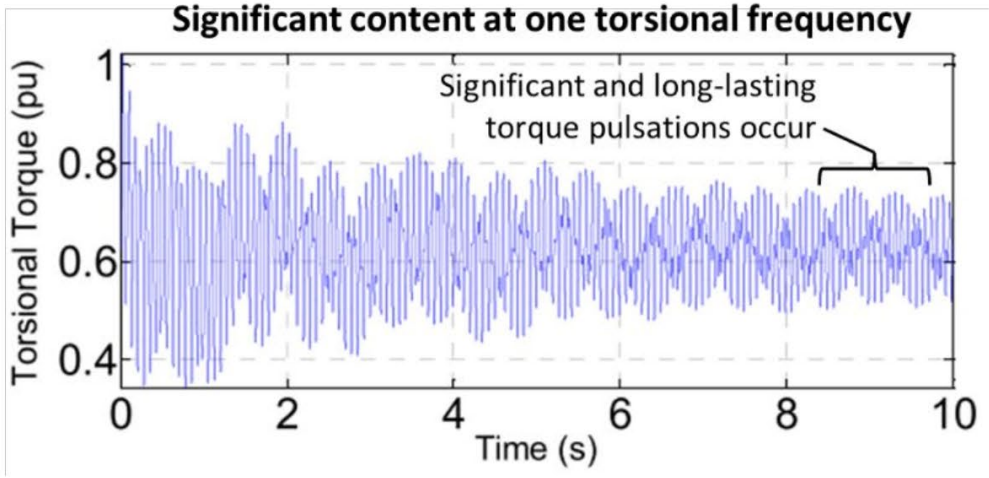
Source: "Power Stabilization for AI Training Datacenters"
Microsoft, OpenAI, NVIDIA

Stability Risks: Forced Oscillations

- Risk is highest when forced oscillation frequency matches: inter-area modal frequencies (can affect entire interconnection) or turbine-generator torsional modal frequencies (can cause shaft fatigue)

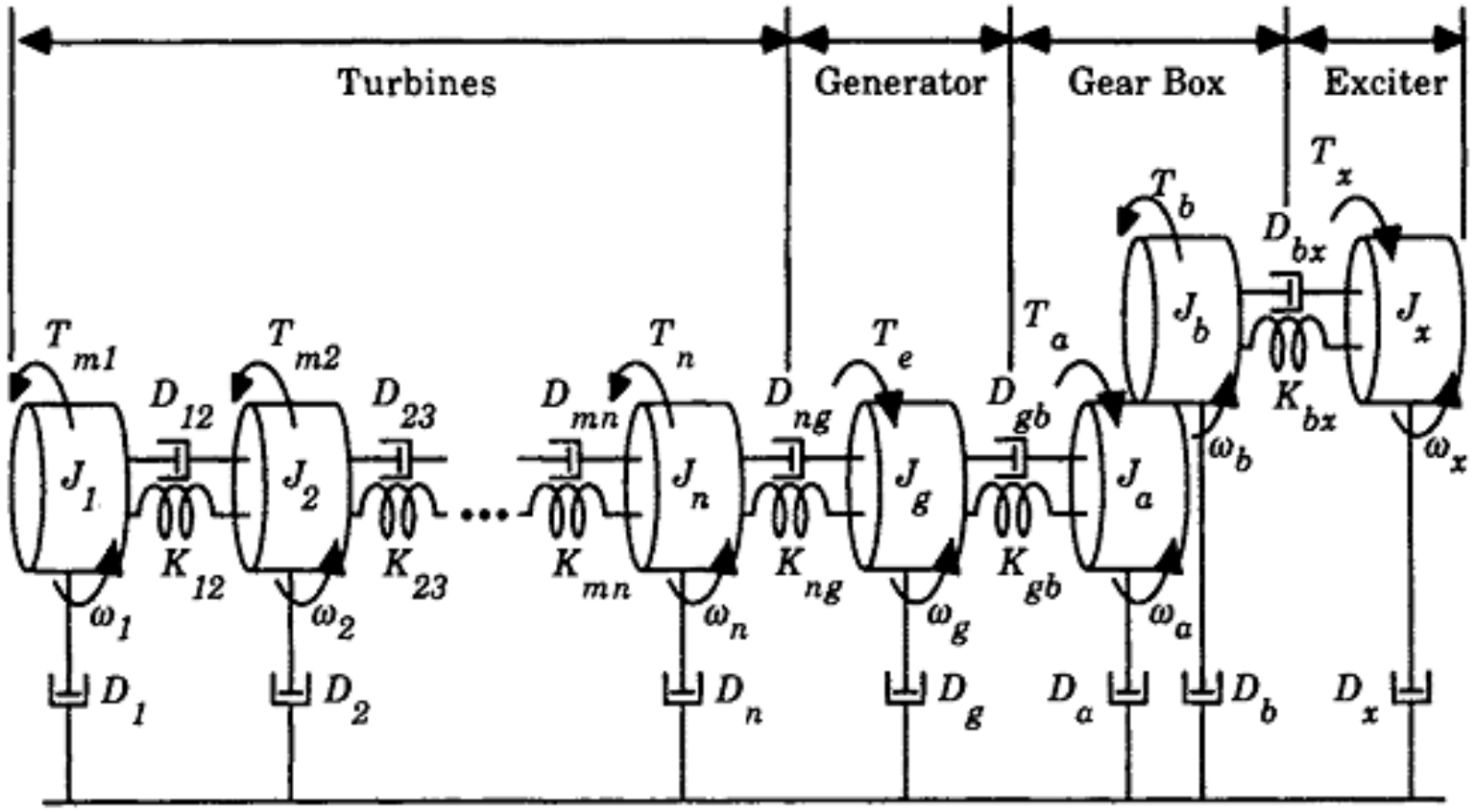
Torques Produced in a Steam Turbine for EAF Loads That Do Not (Left) and Do (Right) Contain Frequency Content at the Steam Turbine's Torsional Modal Frequency





CESI Work for Saudi Electric (SEC)

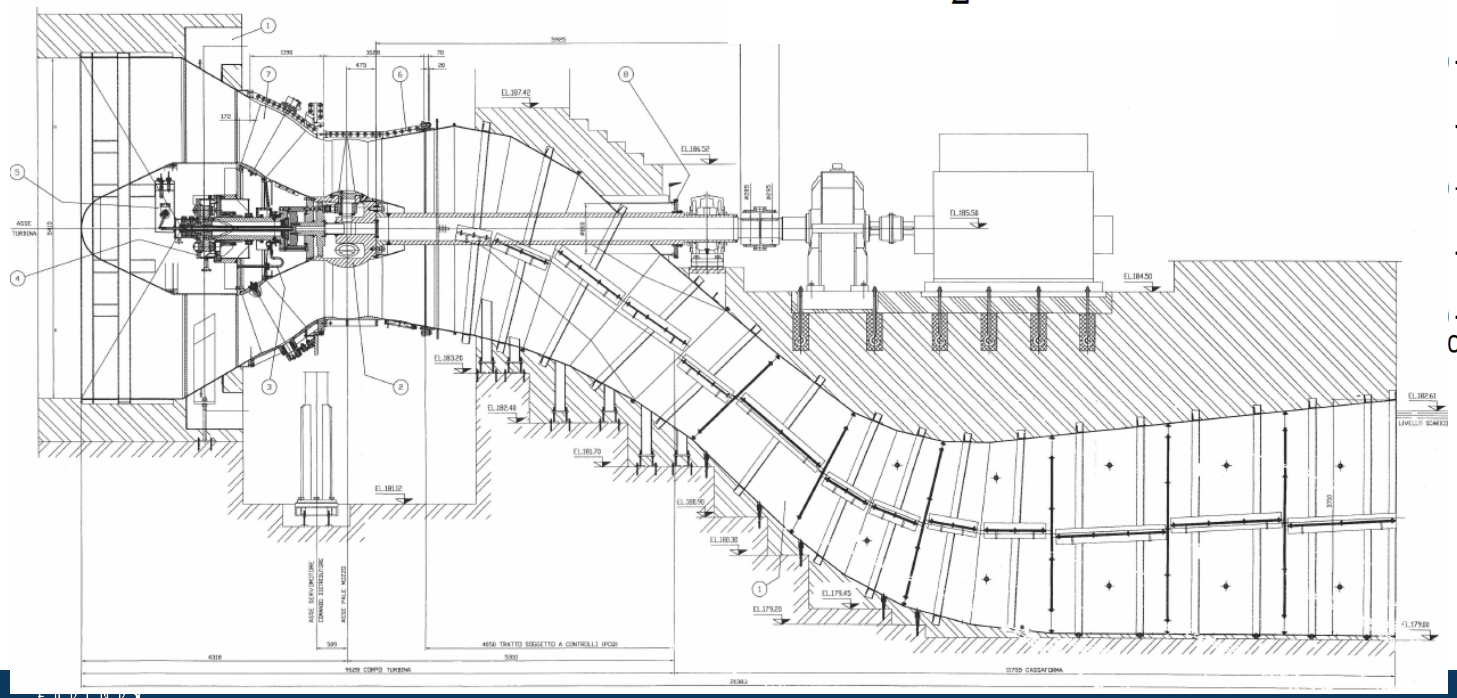
Evaluation of load transient interactions with large generation load

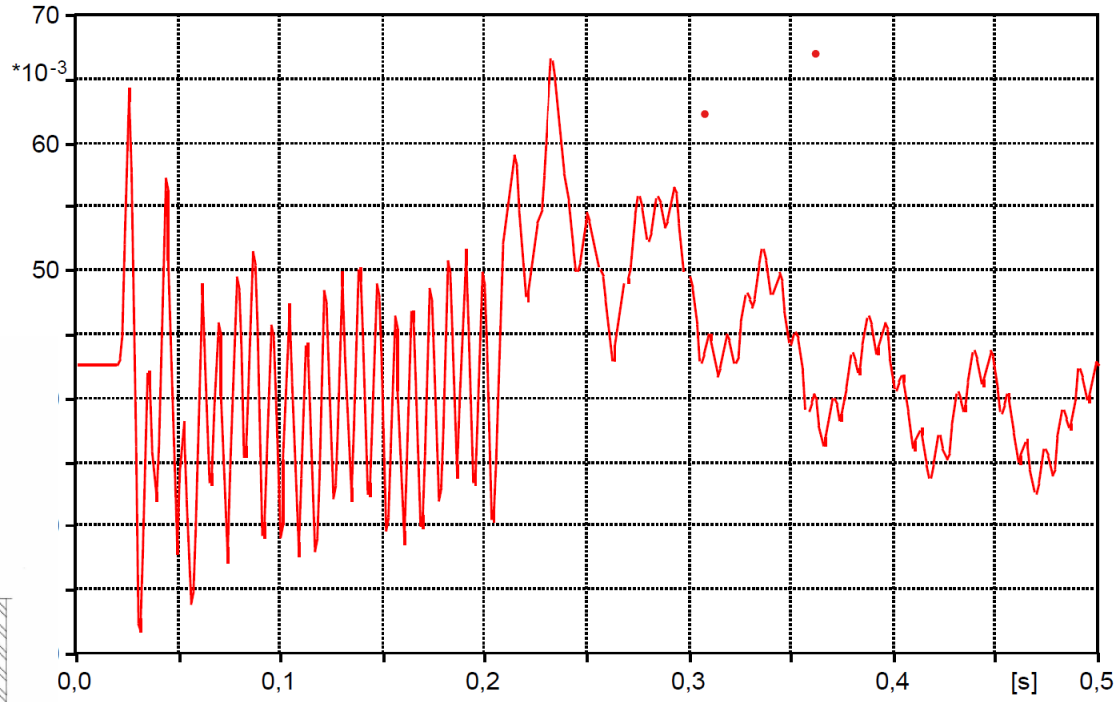


CESI Electromechanical Study for Semenza (Italy) Generation Equipment

- COMSOL Analysis Software

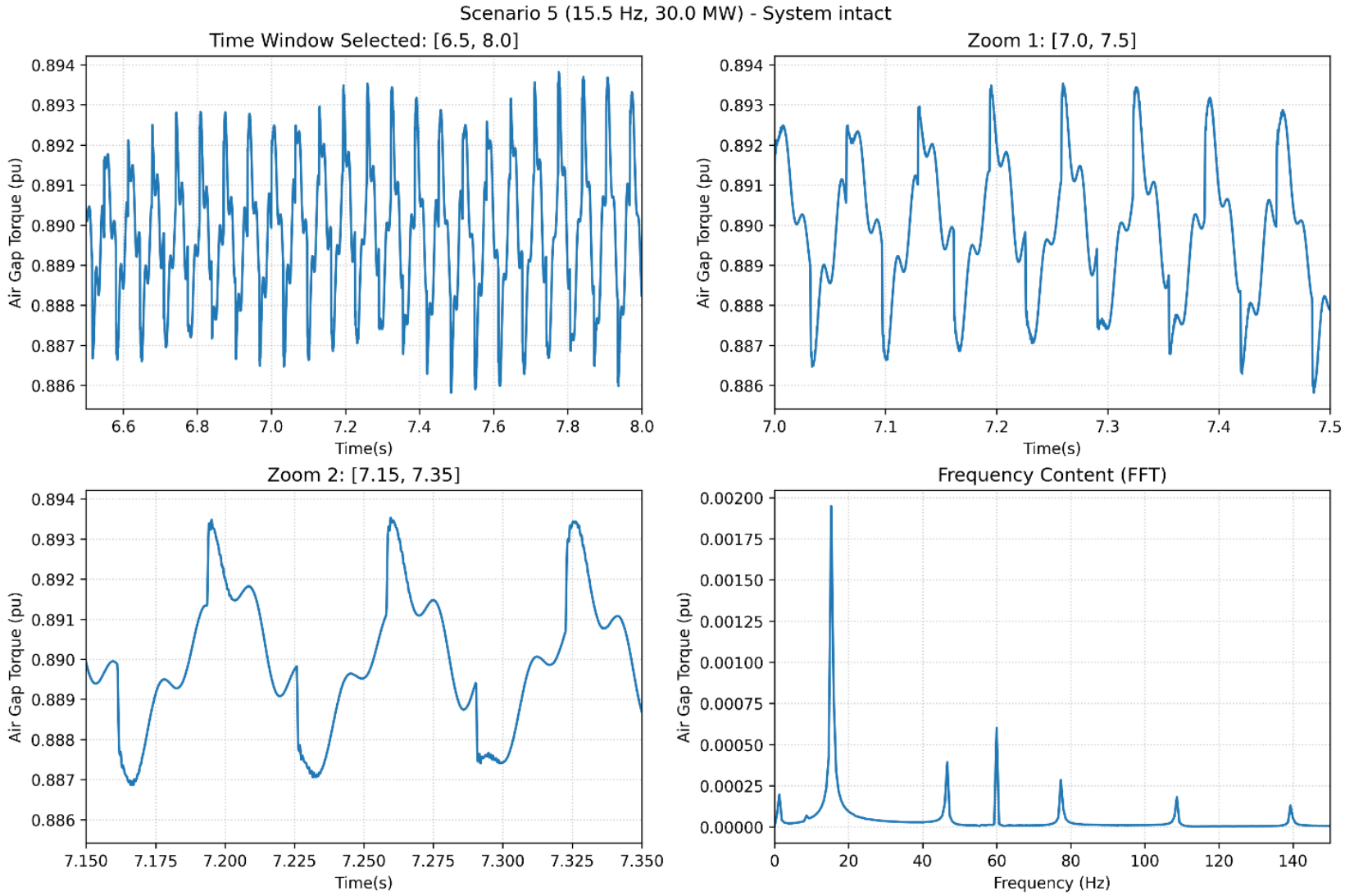
$$J = M \cdot \frac{R_e^2 + r_i^2}{2} = 2700\ kg\ m^2$$



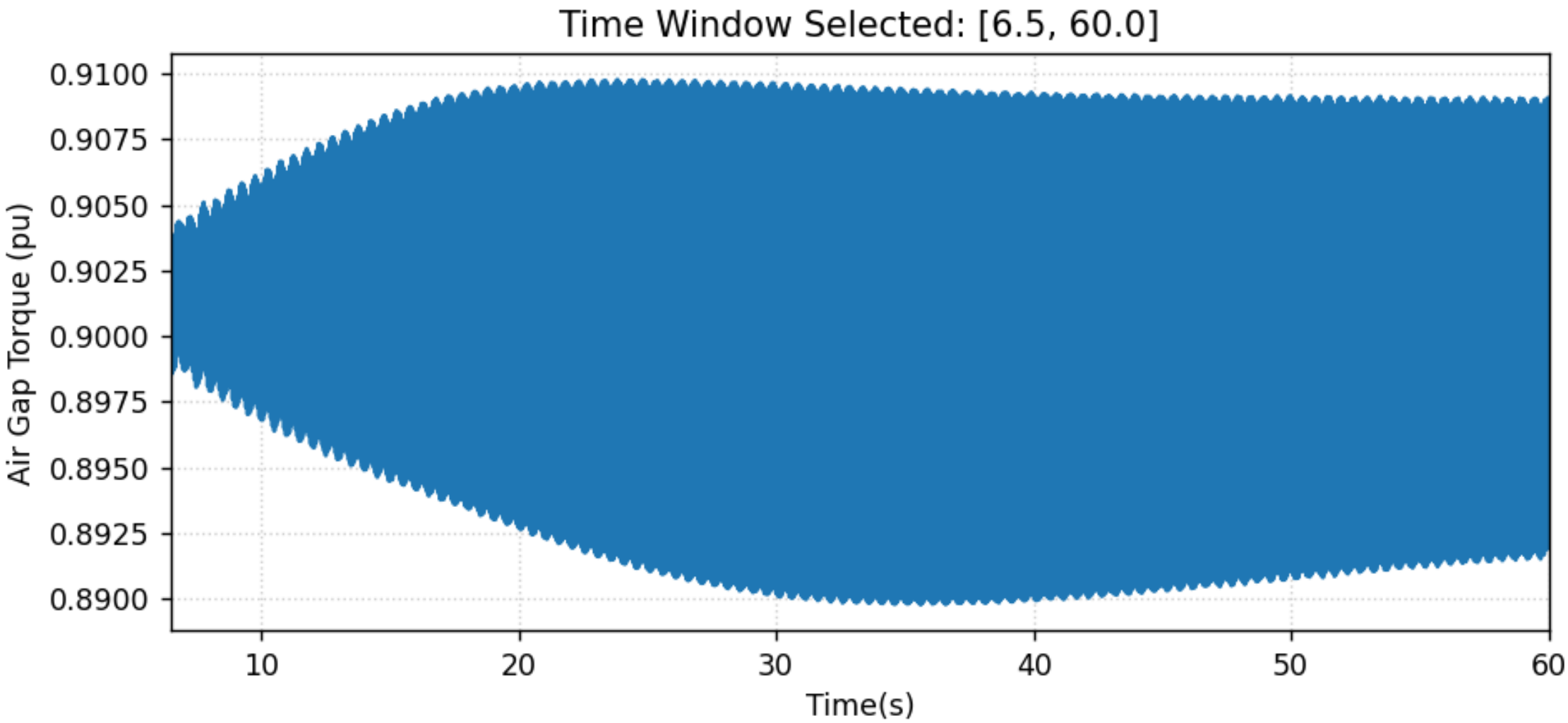


Maximum Torque 66884 N-m

Generator Torque off from Resonance Frequency

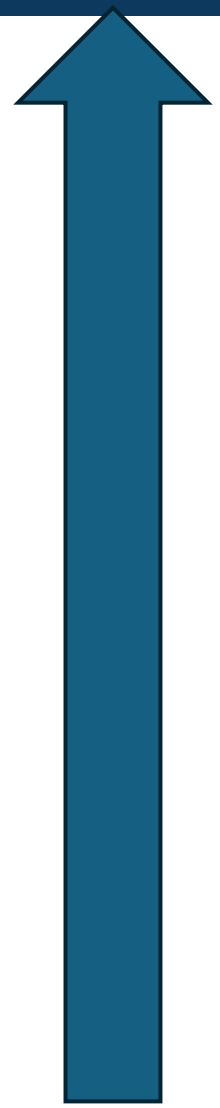


Generator Torque at Mechanical Resonance



Data Center Power Quality Concerns

- **Torsional frequency (10-120 Hz) load variations**
  - The amount of variation (MW at certain frequencies) would case excitement to mechanical shaft vibrations
- **Low voltage ride through (LVRT)**
  - During a voltage sag, the amount of load (MW) drop out (transfer to generation), without causing another (N-1-1) condition
- **Ramp rate**
  - How fast (MW/Min) can the datacenter servers add load to the system
- **Harmonics**
  - Are the IEEE 519 harmonic current limits sufficient to manage harmonic voltages at the PCC
- **Flicker**
  - How much load variation (MW at 10 Hz) would cause too much flicker levels (Pst > 0.36)



High Risk

Medium Risk

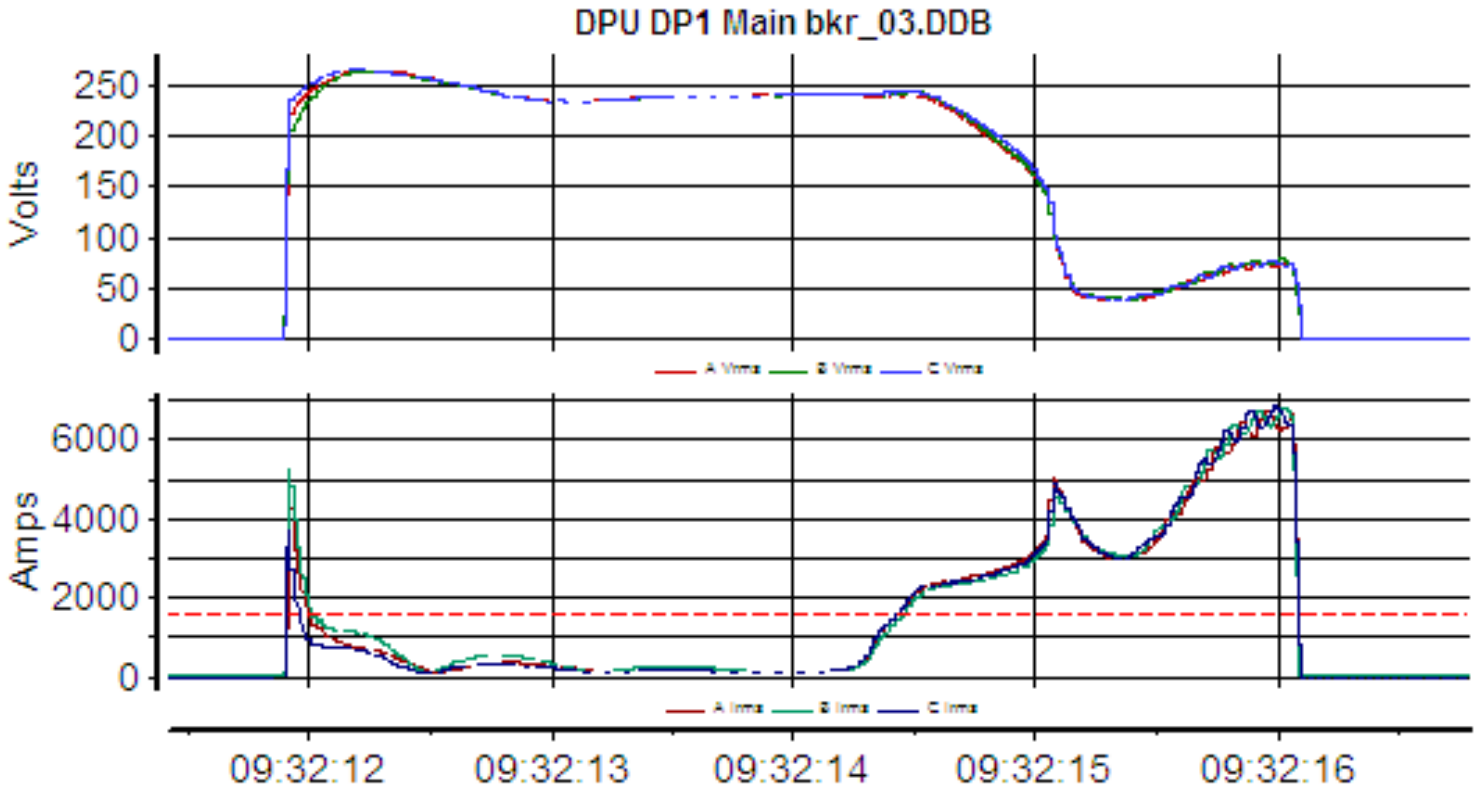
Low Risk

Dealing with Issues on the Server Level

Generator Loading Failure

While testing for inrush, the main circuit breaker from the standby generator tripped.

Fortunately the event was captured by the power disturbance meter.

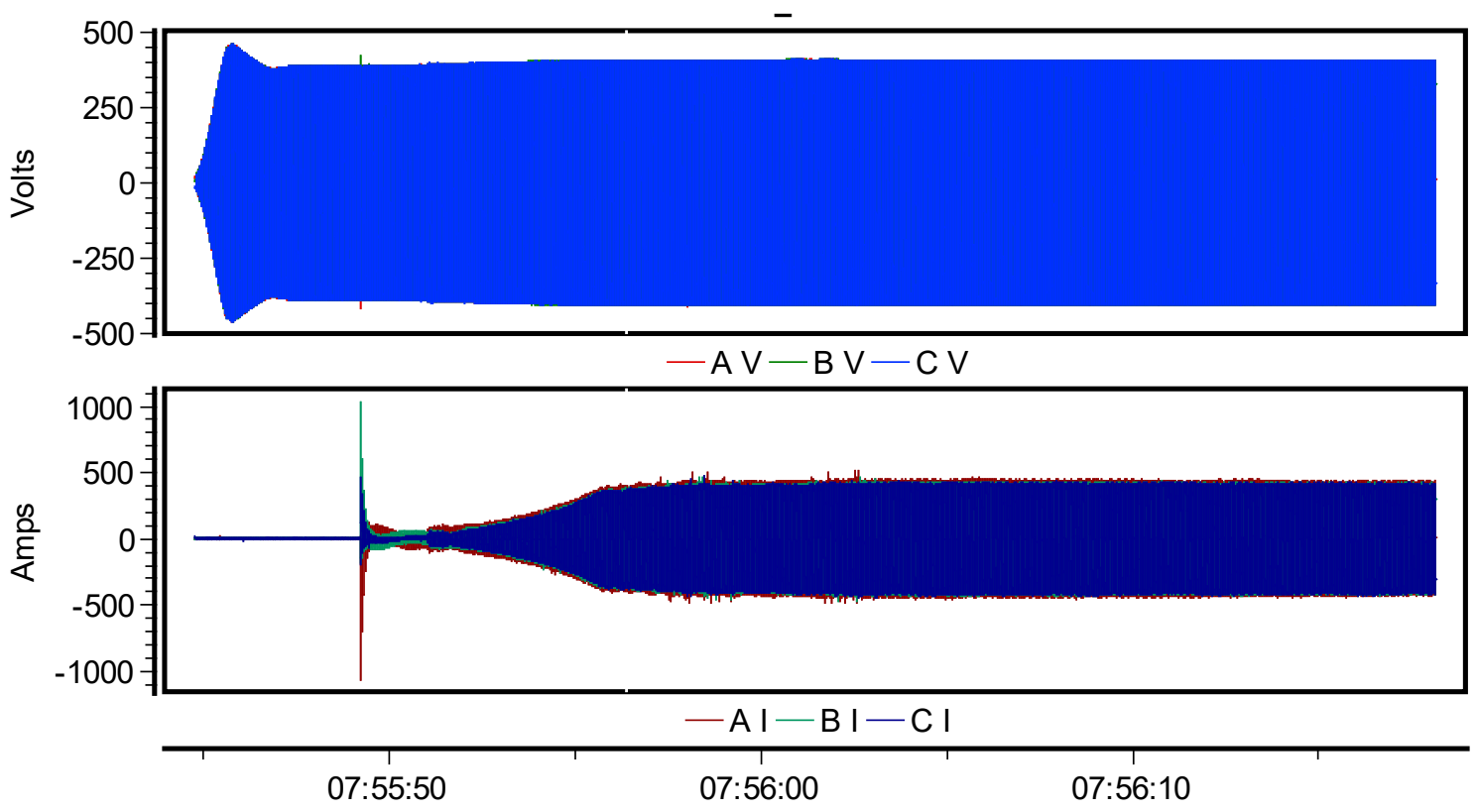


Generator Specifications

- Full Load Acceptance
  - Voltage Dip 39.6%
  - Recovery Time 3.1 Seconds
  - Frequency Dip 7.4%
  - Recovery Time 5.6 Seconds
- Frequency decrease sheds motor load
- Voltage decrease sheds resistive load
- But it can’t shed electronic loads !!

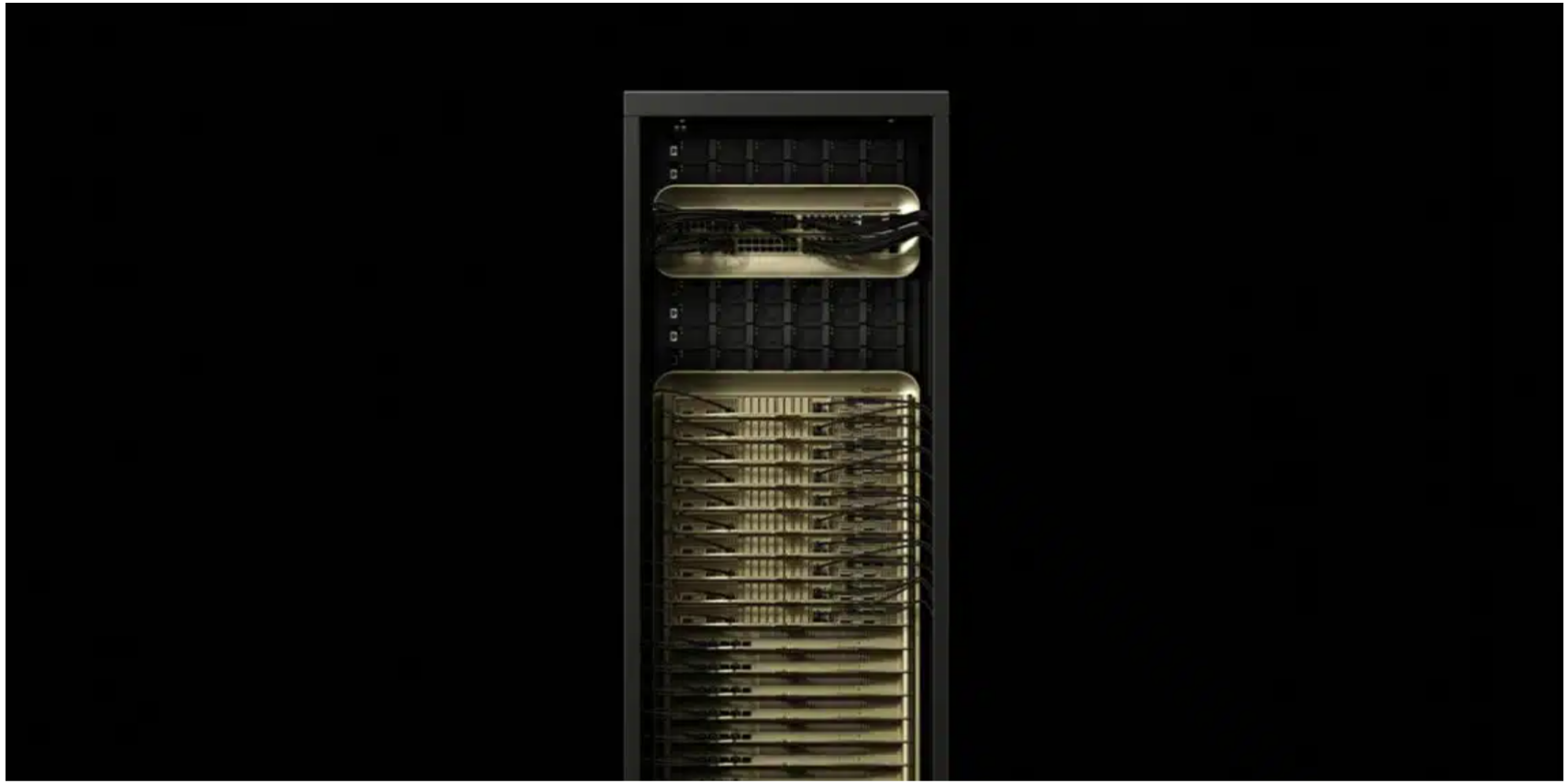
Generator Graduated Load Pickup (Modified)

- Generator Starts (Voltage builds)
- Load transfers (open transition, inrush current)
- Load pickup



NVIDIA GB300 Server

- Rack level solutions
- Server level solutions



NVIDIA unveiled its latest GB300 server, which is slated for launch in the second half of 2025. A notable feature of this server is its integration of a supercapacitor into its power system design.

The built-in supercapacitor in NVIDIA's GB300 is primarily designed to provide a stable power supply environment required by AI and cloud computing servers.

UPS Level Solutions

Vertiv Advanced UPS for AI Workloads

VERTIV.

White paper

Advanced UPS controls for AI workloads management

Enabling stable power protection in high-performance computing environments



32

Vertiv Illustration of AI Power Cycling

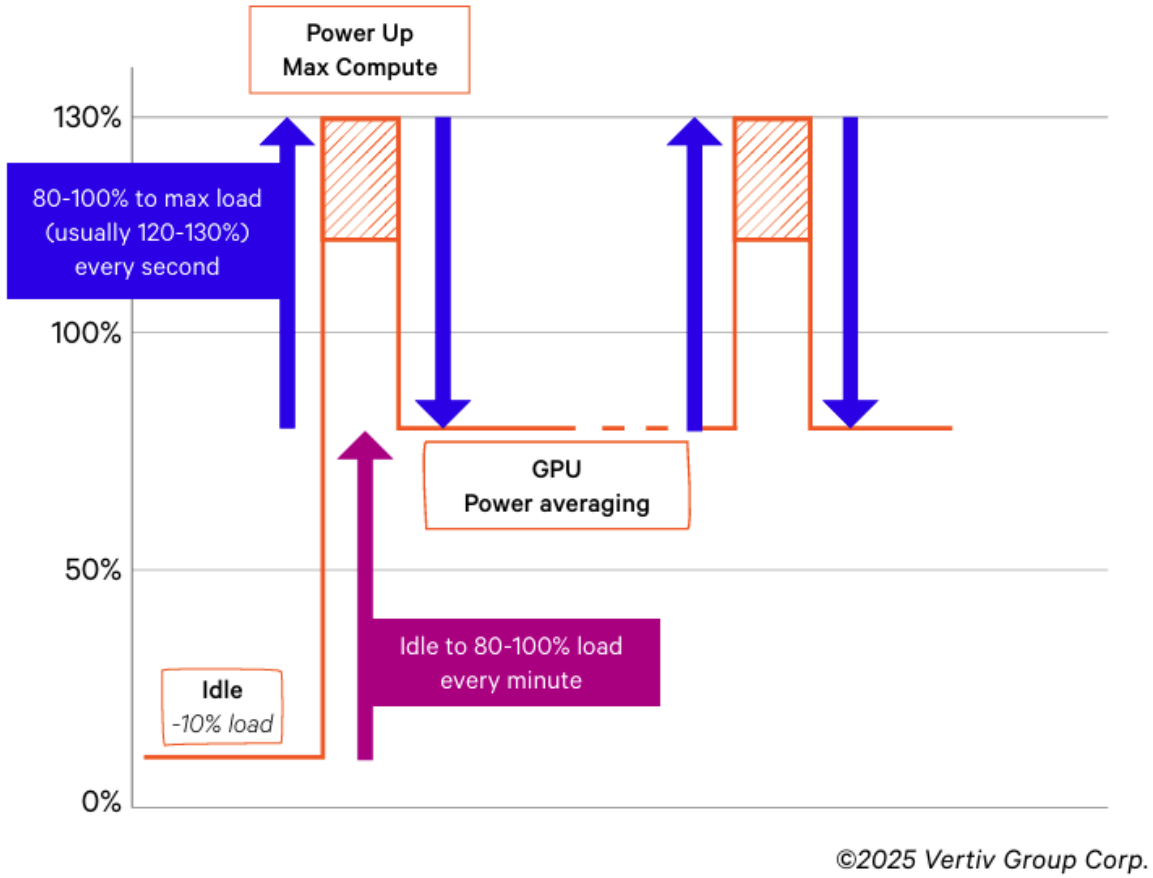


Figure 1. AI workloads' power consumption profiles fluctuate in milliseconds.
Source: Vertiv

The diagram illustrates a representative AI load pattern. System cycles rapidly power up to maximum compute levels, often exceeding 100% nominal load, then quickly drop to a graphics processing unit's (GPU's) lower-averaged power state. This behavior repeats frequently, creating power patterns that are both sharp and regular.

Battery Saving Mode

“Battery Shield” mode of operation

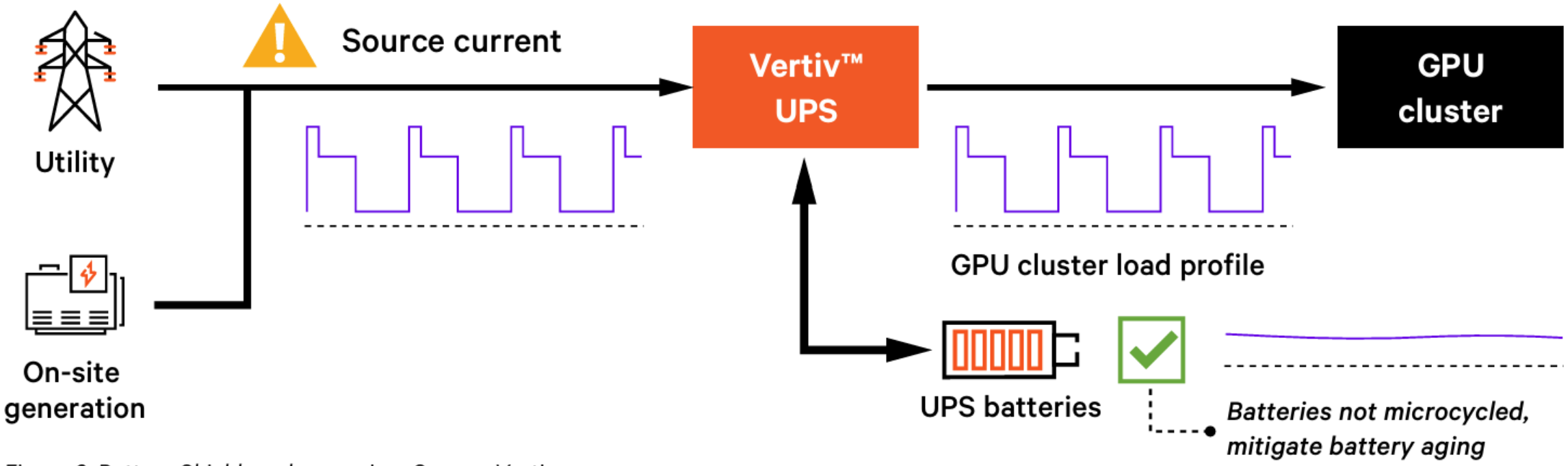


Figure 2. Battery Shield mode overview. Source: Vertiv

©2025 Vertiv Group Corp.

34

Power Smoothing Mode

“Input Power Smoothing” (IPS) mode of operation

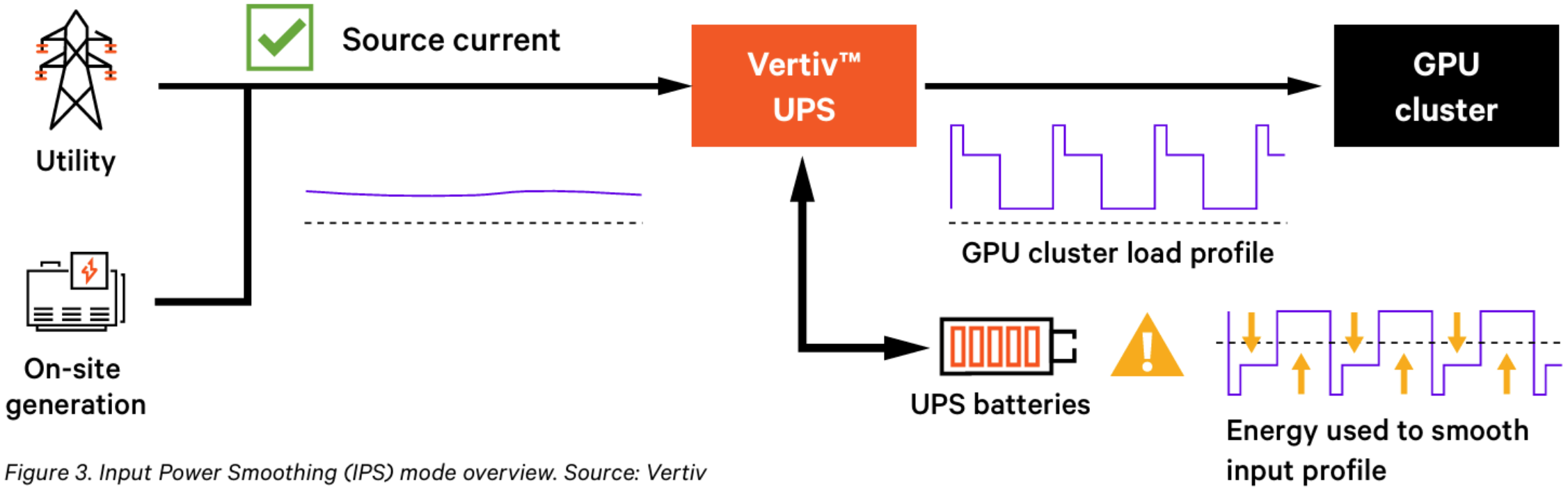


Figure 3. Input Power Smoothing (IPS) mode overview. Source: Vertiv

35

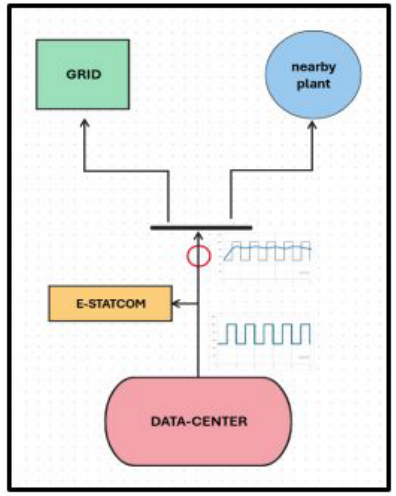
Facility Level Solutions

Siemens E-STATCOM

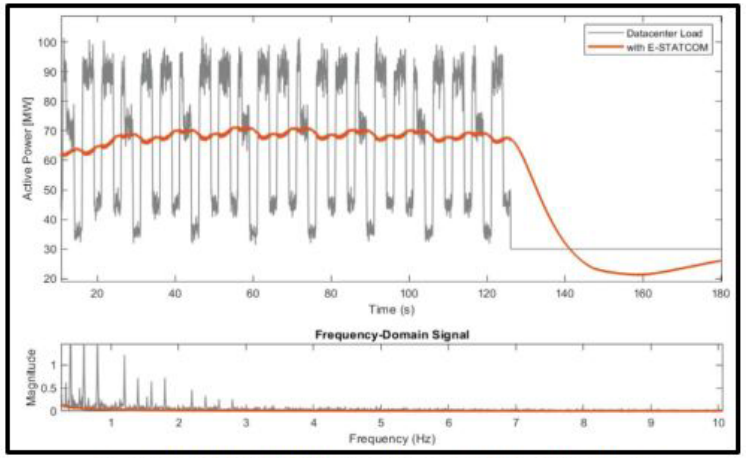
- Speed of response (frequency)
- Depth of response
- Control reliability
- Unproven

Siemens Energy E-STATCOM Solution for AI Datacenter Load Fluctuations

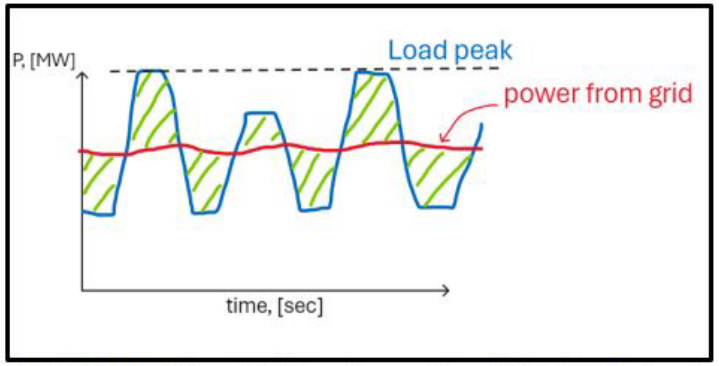
© Mohammad Hammad



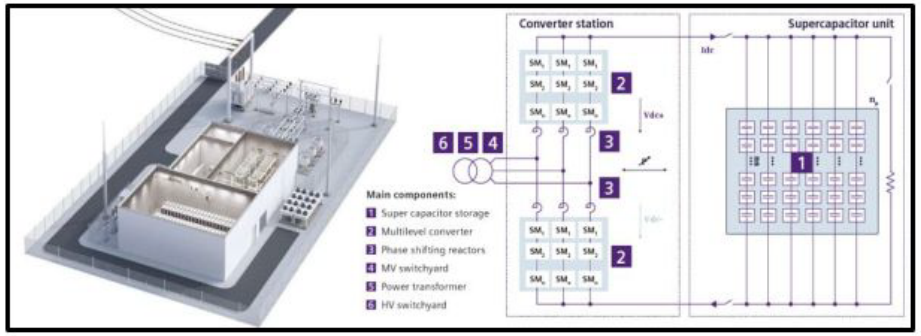
E-STATCOM Mitigates Risk on Nearby Plant



Example of E-STATCOM Smoothing Out AI-Training Load



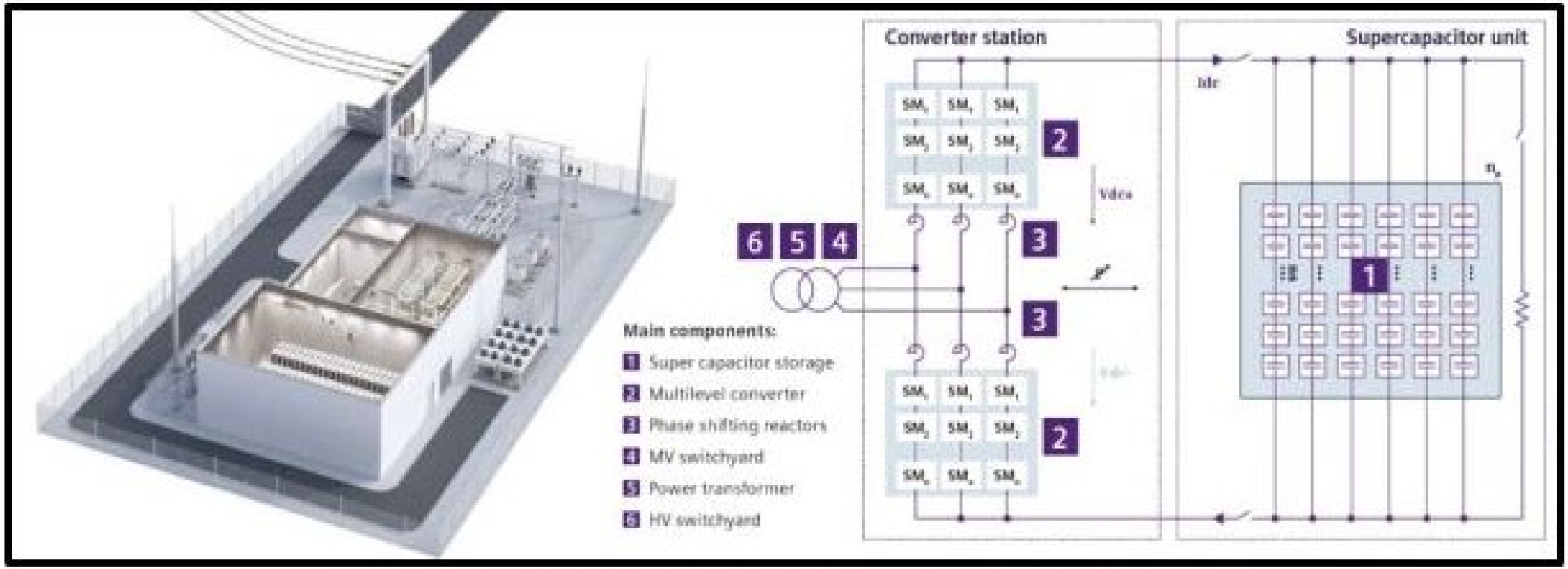
E-STATCOM Stabilizes Grid Power Demand from Highly Variable Loads



Siemens Energy Enhanced STATCOM for Data Centers

37

Siemens E-STATCOM

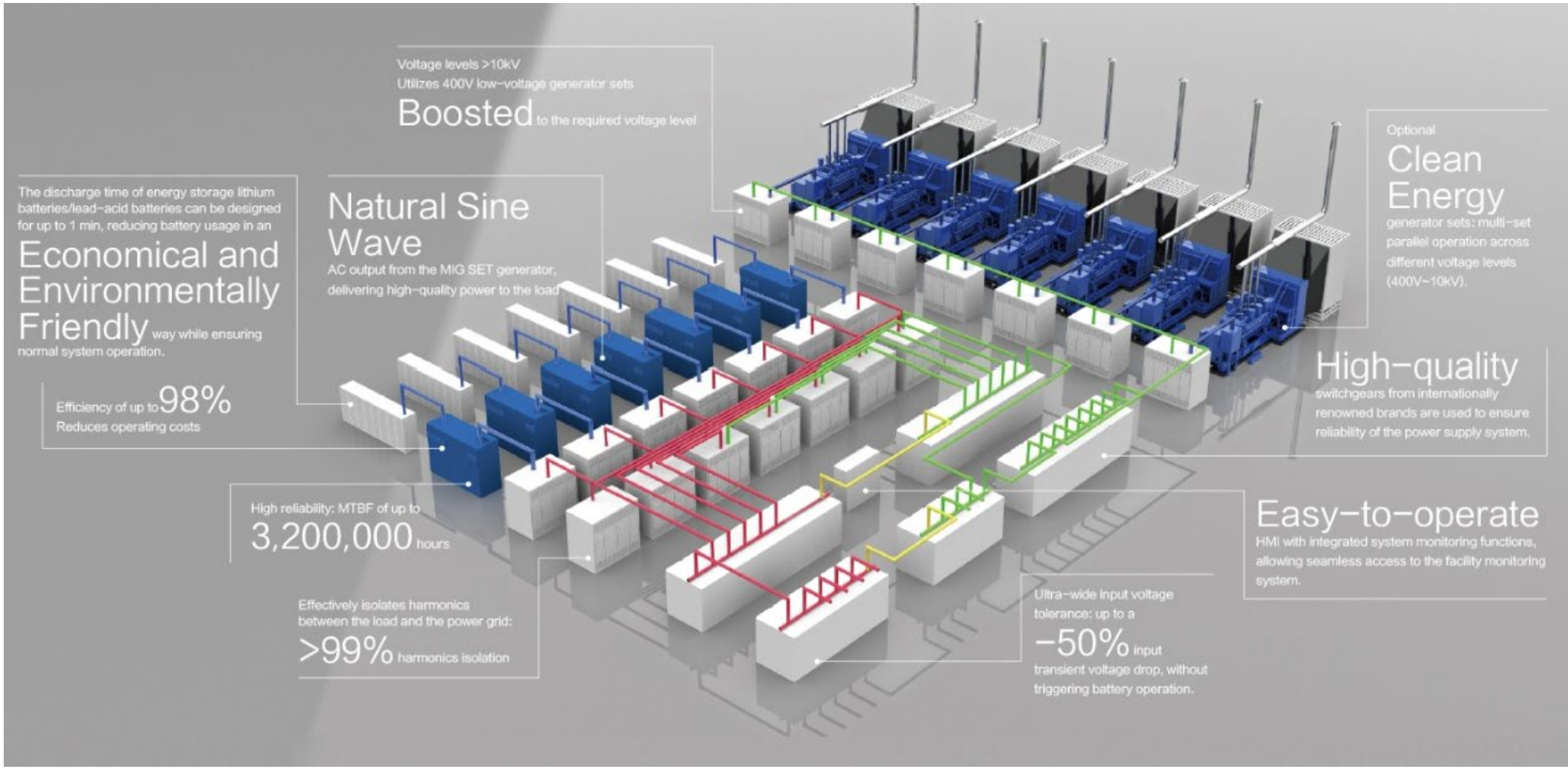


Siemens Energy Enhanced STATCOM for Data Centers

38

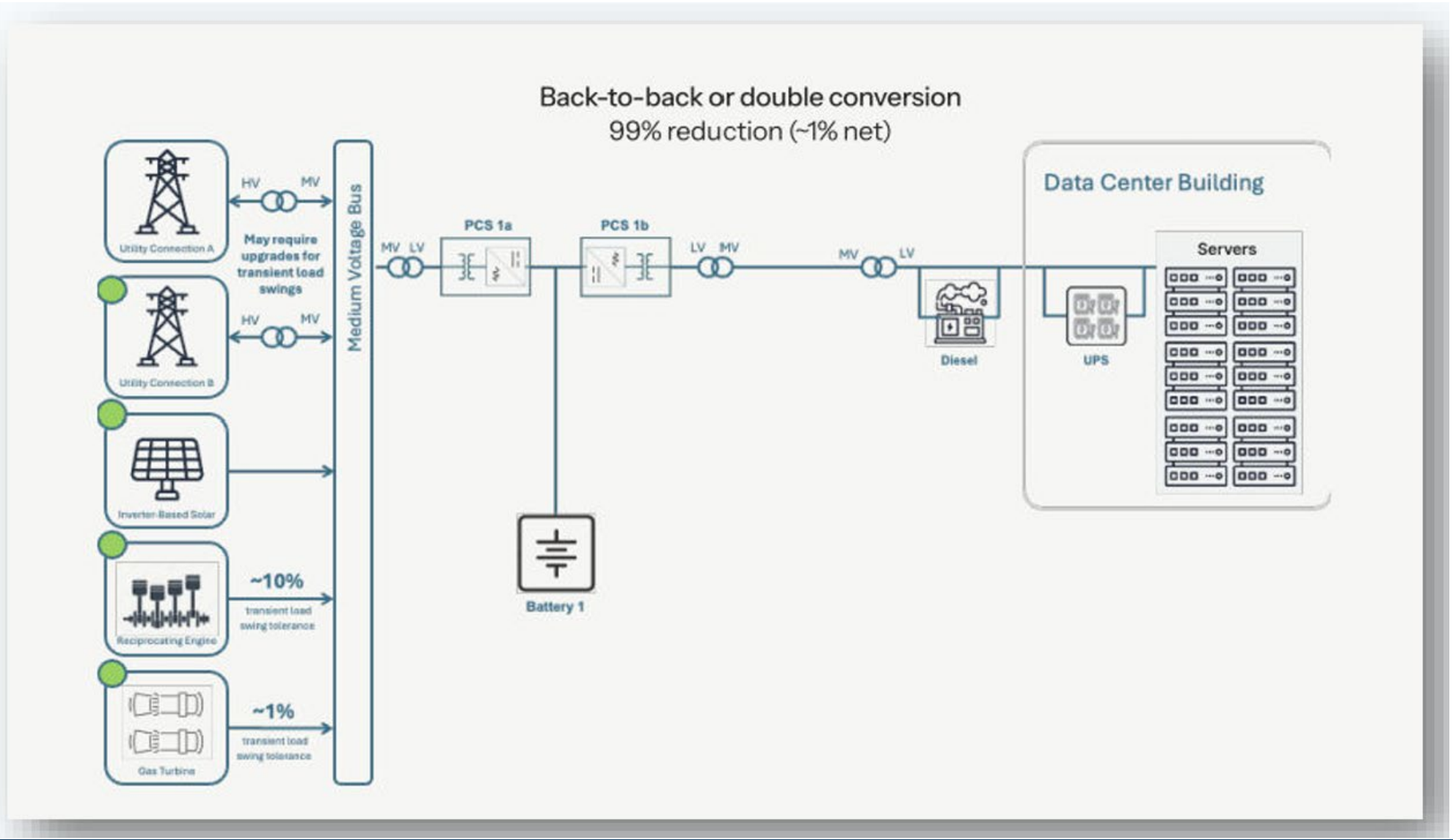
MV UPS System

- Load sharing of modules
- Ability to smooth load shapes
- LVRT Capability
- High losses



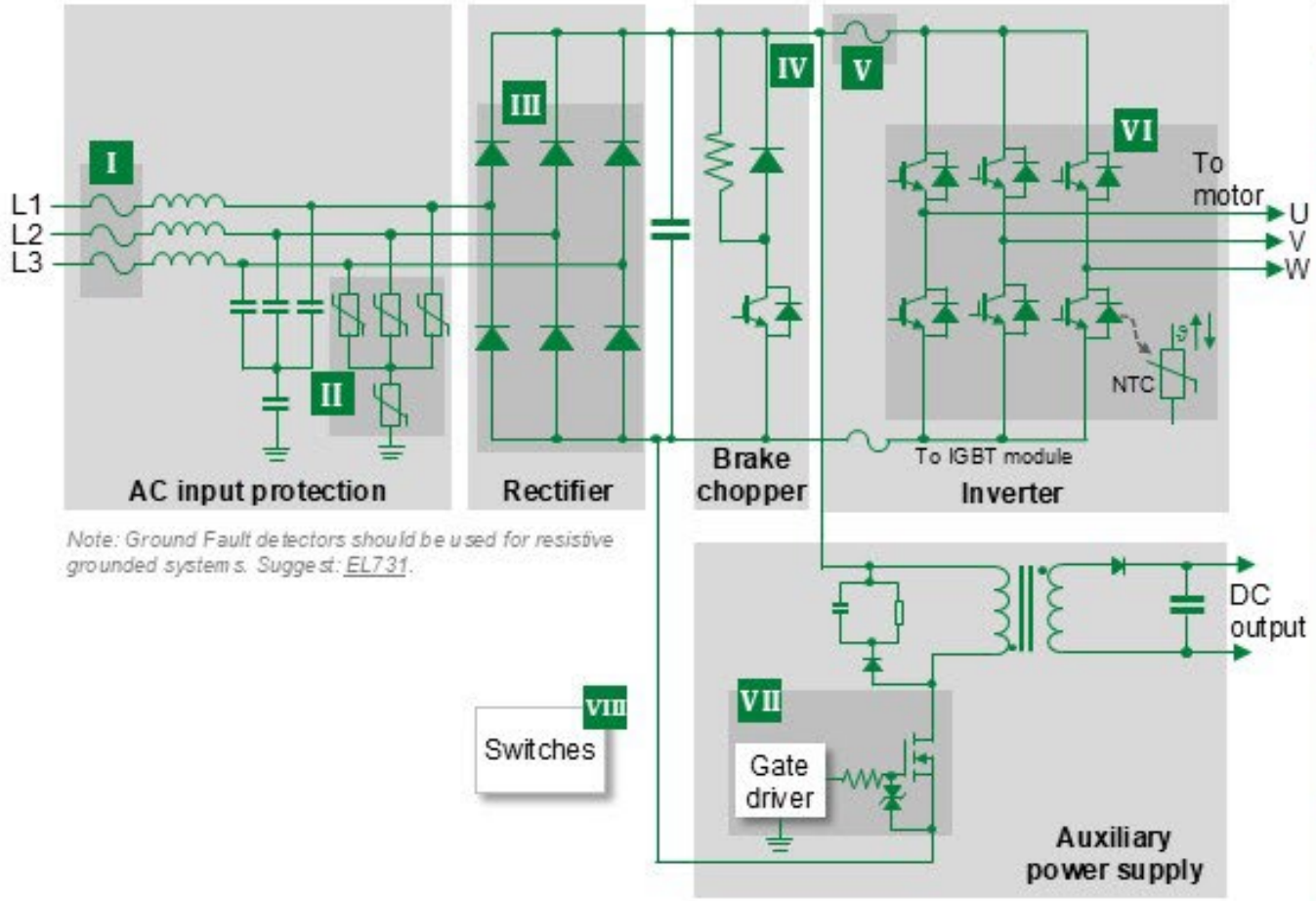
39

Flexgen Back to Back Conversion BESS System



40

How are we going to verify the viability of these solutions?

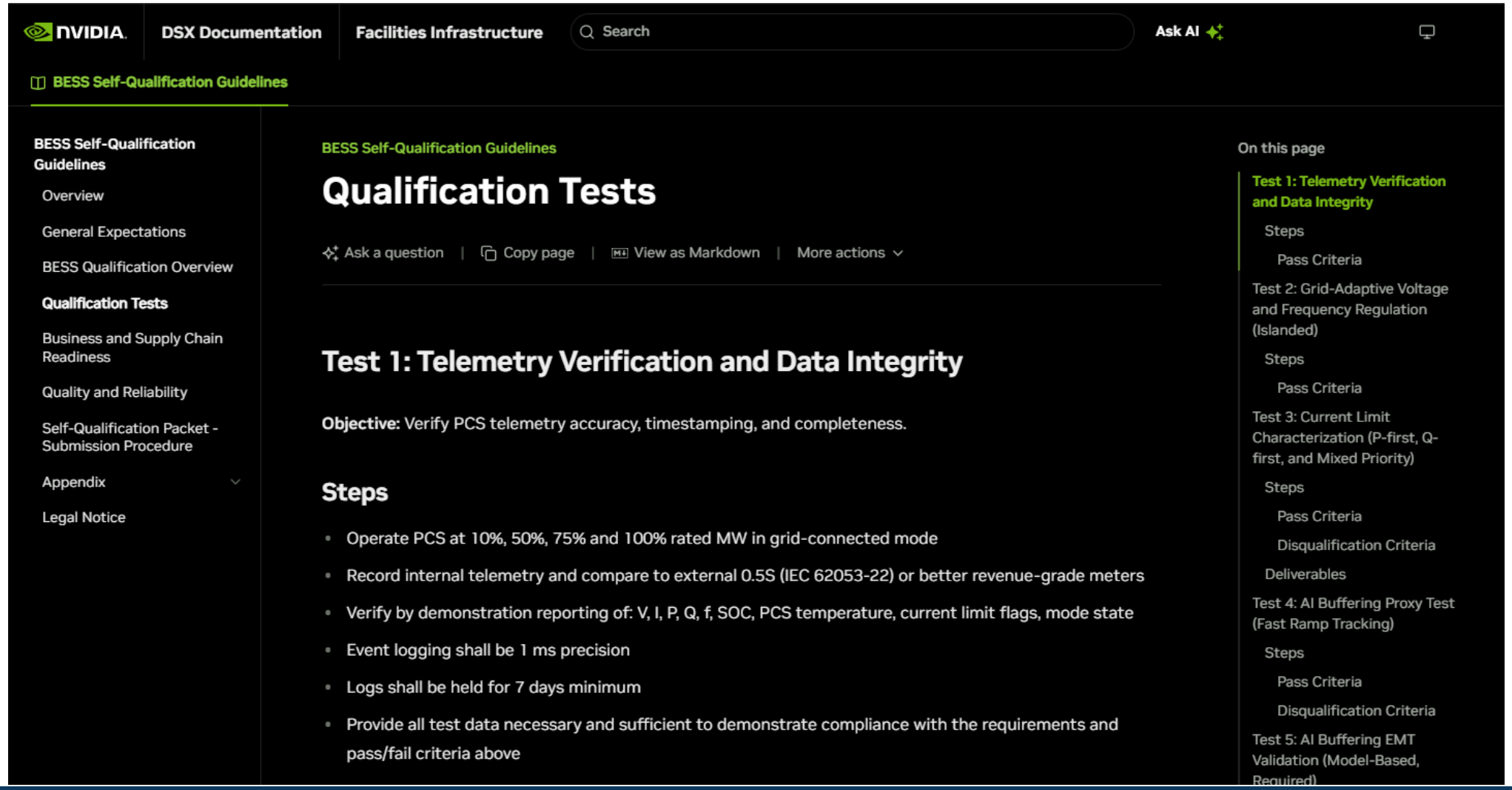


Note: Ground Fault detectors should be used for resistive grounded systems. Suggest: EL731.

	Technology	Product Series
I	Fuse	JLS, JLLS, JLLN, LDC, 606, 504, 505, 607
	Fuseholder	LFT, LFJ
II	MOV	TMOV, UltraMOV
III	Rectifier Diode	AC Bridges, Diode Modules, Discrete Devices
	Rectifier Stack	High Power Stacks
IV	E2/E3-Module *OR* SMPD	Boost Chopper IGBT Modules *OR* IXA20RGxx, IXA30RGxx, IXA40RGxx
V	Semiconductor Fuse	PSR, L50QS, L70QS, L60QS
VI	IGBT Module *OR* SMPD	XPT IGBT Modules, Six Pack IGBT Modules, CBI Modules *OR* IXA20PGxx, IXA30PGxx, IXA40PGxx
	IGBT Discrete	XPT IGBT Discrete
	NTC	USUR1000, SM
	TVS Diode	SMBJ, SMF4L, 1.5SMC
VII	SiC MOSFET *OR* Si HV MOSFET *OR* HV IGBT	SiC MOSFET *OR* Si HV MOSFET *OR* HV IGBT
	Gate Driver	IXD_609, IX4310T, IX4352NE
	TVS Diode	SMF, SMFA
VIII	Switch	TDA, RTE, RTA, AYZ, KSC2, KSC3, KSC4

NVIDIA BESS Self-Qualification Guidelines and Tests

https://docs.nvidia.com/dsx/facilities-infra/bess/qualification-testsNVIDIA DSX Documentation



Test 2: Grid-Adaptive Voltage and Frequency Regulation (Islanded)

https://docs.nvidia.com/dsx/facilities-infra/bess/qualification-testsNVIDIA DSX Documentation

Objective: Demonstrate stable operation with no external grid reference.

Setup: Isolated test bus with configurable resistive/inductance/capacitance (RLC) load bank.

Steps

- Black start onto dead bus (if Test 10 not yet done, run reduced voltage)
- Hold voltage and frequency within the system's defined stability limits at a steady load
- Apply load steps: +10%, +20%, -20% of PCS rated MW
- Record V, I, P, Q, f, and control mode state throughout the test
- Provide all test data necessary and sufficient to demonstrate compliance with the requirements and pass/fail criteria above.

Pass Criteria

- Stable V/f with no sustained oscillation
- Voltage and frequency return to their steady-state range in a timely, well-damped manner, with no evidence of control hunting or marginal stability
- No protective trip

Test 5: AI Buffering EMT Validation (Model-Based, Required)

https://docs.nvidia.com/dsx/facilities-infra/bess/qualification-testsNVIDIA DSX Documentation

Objective: Validate PCS stability and control robustness under extreme weak-grid conditions representative of faulted, partially islanded, or switching-dominated AI campus scenarios.

Partner Provides

- EMT model of PCS + controls (compiled or encrypted acceptable, but must run)
- dq impedance curves vs frequency
- Nyquist or passivity evidence

Required EMT Case

- **SCR:** 2.0
- **Grid impedance:** Sweep from X/R ratio = 2 to 10, representative of inverter-dominated grids
- **Topology:** Grid-connected with upstream source modeled as weak voltage source
- **Load:** Constant Power Load representative of IT/compute with clearly defined ramp characteristics shall be used

Disturbances to Apply

- AI buffering proxy ramps
- At least one grid disturbance event (voltage dip, impedance step, or partial islanding)
- Entry into and recovery from PCS current limit

Test 7: LVRT / HVRT Functional Ride-Through (Hardware or HIL)

https://docs.nvidia.com/dsx/facilities-infra/bess/qualification-testsNVIDIA DSX Documentation

Objective: Prove ride-through behavior aligned to IEEE 2800 baseline.

Steps

- Apply voltage sag and swell profiles at AC terminals (grid simulator or HIL) at both weak-grid (SCR ≤ 3) and strong-grid (SCR ≥ 20) configurations:
  - Multiple depth-duration points per IEEE 2800 or utility categories
- Observe whether PCS stays connected and how it prioritizes Q support
- Record V, I, P, Q, f, and protection relay states throughout each ride-through event
- Provide all test data necessary and sufficient to demonstrate compliance with the requirements and pass/fail criteria above

Pass Criteria

- No trip within IEEE envelope or applicable utility/ISO envelope, whichever governs
- Correct trip outside envelope
- Q injection behavior documented and consistent

Test 9: Islanded Operation with Generator Following (Model Based)

https://docs.nvidia.com/dsx/facilities-infra/bess/qualification-testsNVIDIA DSX Documentation

Objective: Validate interaction with turbines or gensets.

Steps

- EMT model with GFM BESS as voltage master
- Generator modeled as droop-following source with realistic governor time constants
- Apply AI load proxy disturbance and show:
  - BESS absorbs fast dynamics
  - Generator picks up slower energy component
- Include N-1 generation event
- Provide all test data necessary and sufficient to demonstrate compliance with the requirements and pass/fail criteria above

Pass Criteria

- No sustained oscillation
- SOC drift controlled (see Test 11)
- Frequency and voltage remain within declared bounds

Summary

- Electrical behavior of emerging large loads during both normal AND abnormal grid conditions represents new challenges for planners and operators
- Operating experience with emerging large loads remains limited
- Large loads may come in different forms, but the rapid growth associated with data centers tends to be the focus on the characteristics and potential risks of the Bulk Electric System (BES)

Using EMT Simulations to Understand, Solve, and Prevent Electrical Power Problems!

EnerNex Headquarters

620 Mabry Hood Road

Suite 102

Knoxville, TN 37932

865-300-6690

www.enernex.com



dmueller@enernex.com