Sandia National Laboratories

Exceptional service in the national interest

VOLTAGE AND FREQUENCY RIDE-THROUGH FOR LARGE COMPUTATIONAL LOADS

State of the Art

Ryan Elliott and Matthew Reno

Electric Power Systems Research

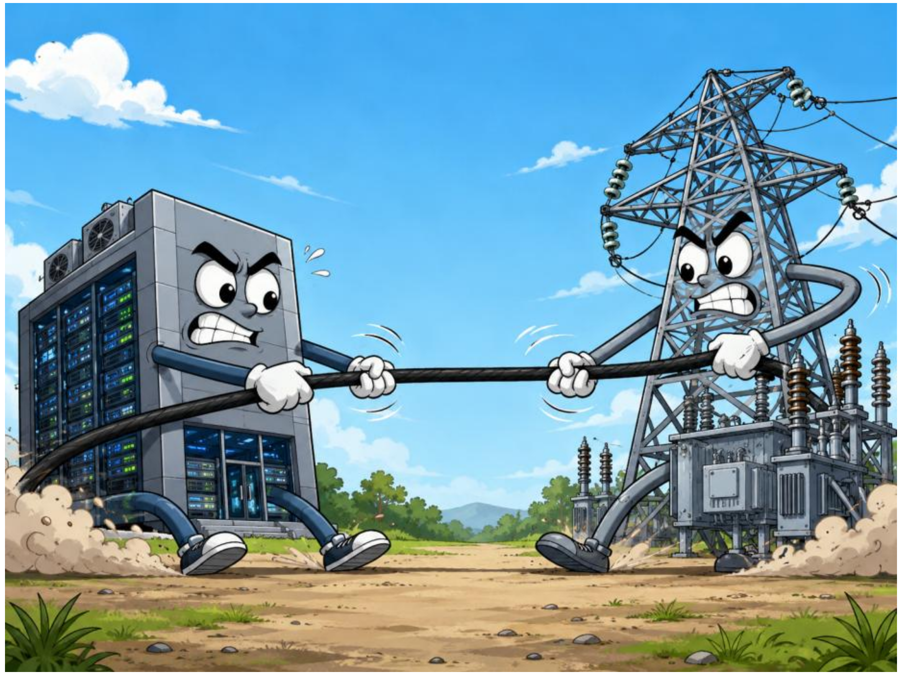
September 14, 2026

U.S. DEPARTMENT of ENERGY

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

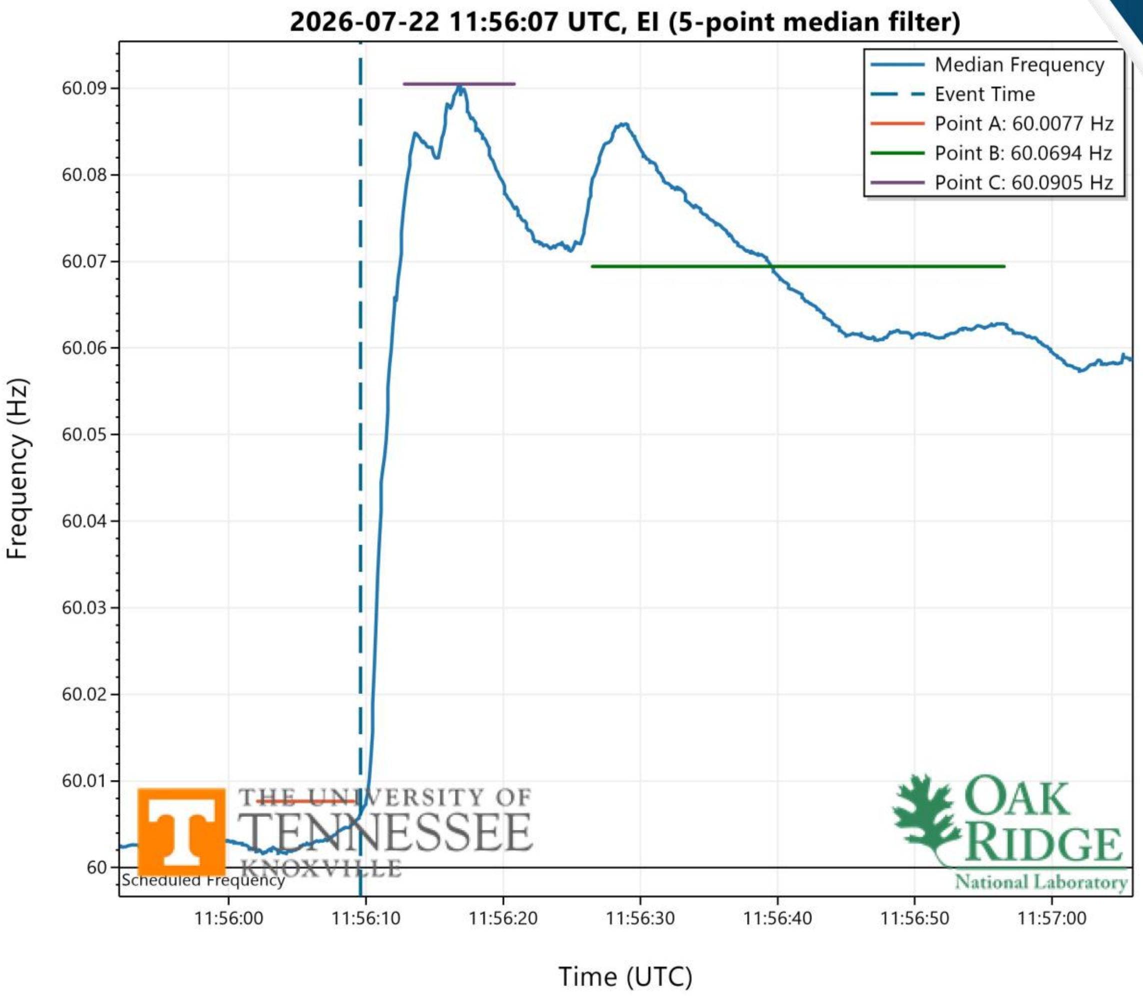
OVERVIEW

- Background
- Enabling Technologies for Voltage Ride-Through
  - E-STATCOM
  - Centralized Battery Energy Storage
  - Series Battery Energy Storage
  - Grid Interactive UPS
  - Innovation in Data Center Power Delivery
- Frequency Ride-Through for Large Computational Loads
- Conclusions



BACKGROUND

- ERCOT identified 26 events between 2023–2025 in which large computational loads tripped during routine voltage disturbances.
    - These events are becoming more frequent and more severe.
- On July 22, 2026, a single line fault in northern Virginia caused ~3.8 GW of data center load to disconnect from PJM within seconds.
- Under stressed system conditions, sudden load loss of this magnitude could trigger cascading trips across the system.
- Today we'll survey technologies that enable data centers to ride through such events.



FNET/GridEye, "Event Report: Event 335377," Power Information Technology Laboratory, University of Tennessee and Oak Ridge National Laboratory, Jul. 22, 2026.. Available here.

TECHNOLOGY COMPARISON PREVIEW

- Estimated one-time costs to achieve NOGRR 282 ride-through compliance for a 100 MW facility.

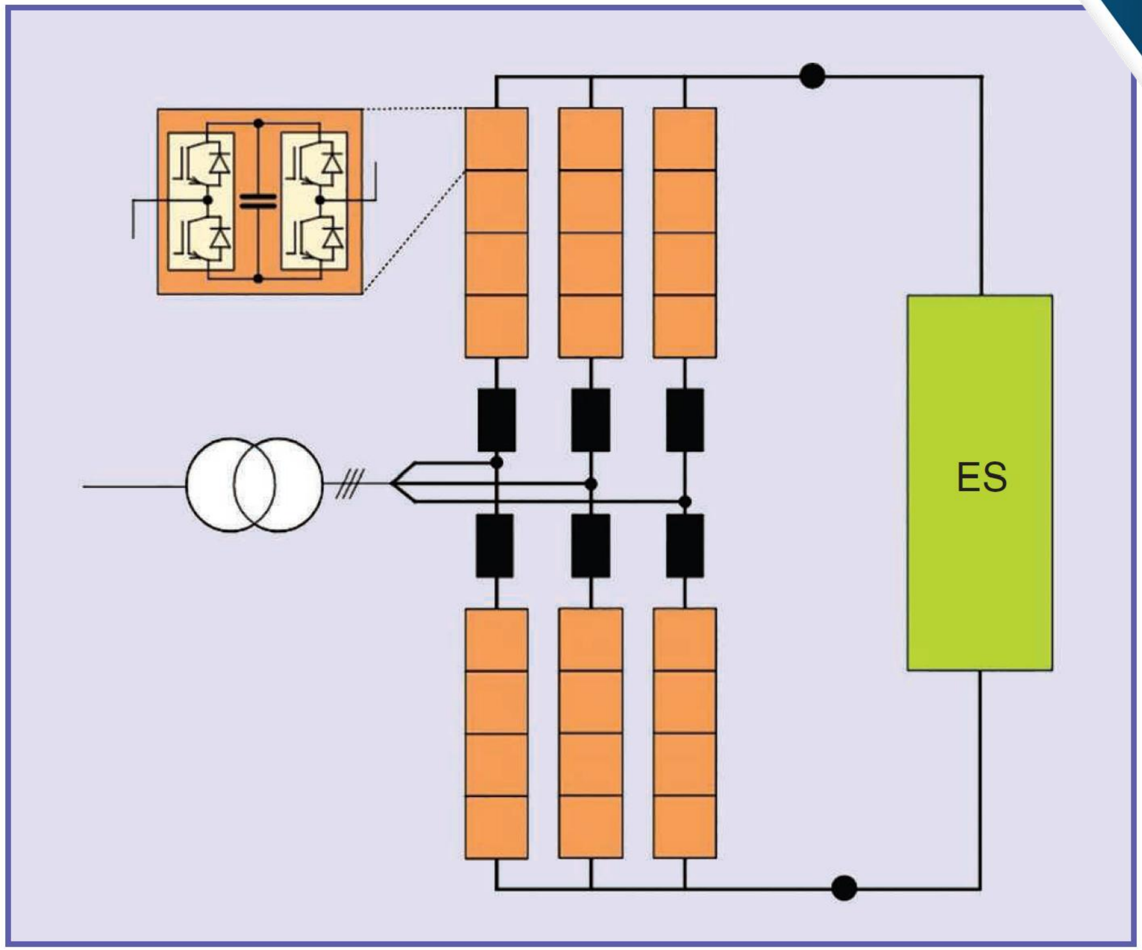
	One-time costs	Impact on facility efficiency	Retrofit possible?	Timeline for at-scale deployment
E-STATCOM	\$25–50M est. for a 100 MW system	Minimal change	Yes	2–3 years (no data center installs yet)
Central BESS	\$35–70M est. for a 100 MW system*	Minimal change	Yes	Available now
Series BESS	\$50–90M est. for a 100 MW system*	Less efficient (conversion losses)	Yes (major equipment additions)	1–2 years (first projects commissioning)
Grid-Int. UPS	\$1–15M est. for a 100 MW facility†	No change	Yes (potentially firmware only)	Available now
DC Architecture	Not separable from facility cost	More efficient (fewer conversion stages)	No (requires full redesign)	3–5 years (simulation and lab testing only)

*Cost scales with duration; 2–4 hour system.

†Leverages existing UPS infrastructure. Low end reflects firmware upgrades only; high end includes battery replacement.

WHAT IS AN E-STATCOM?

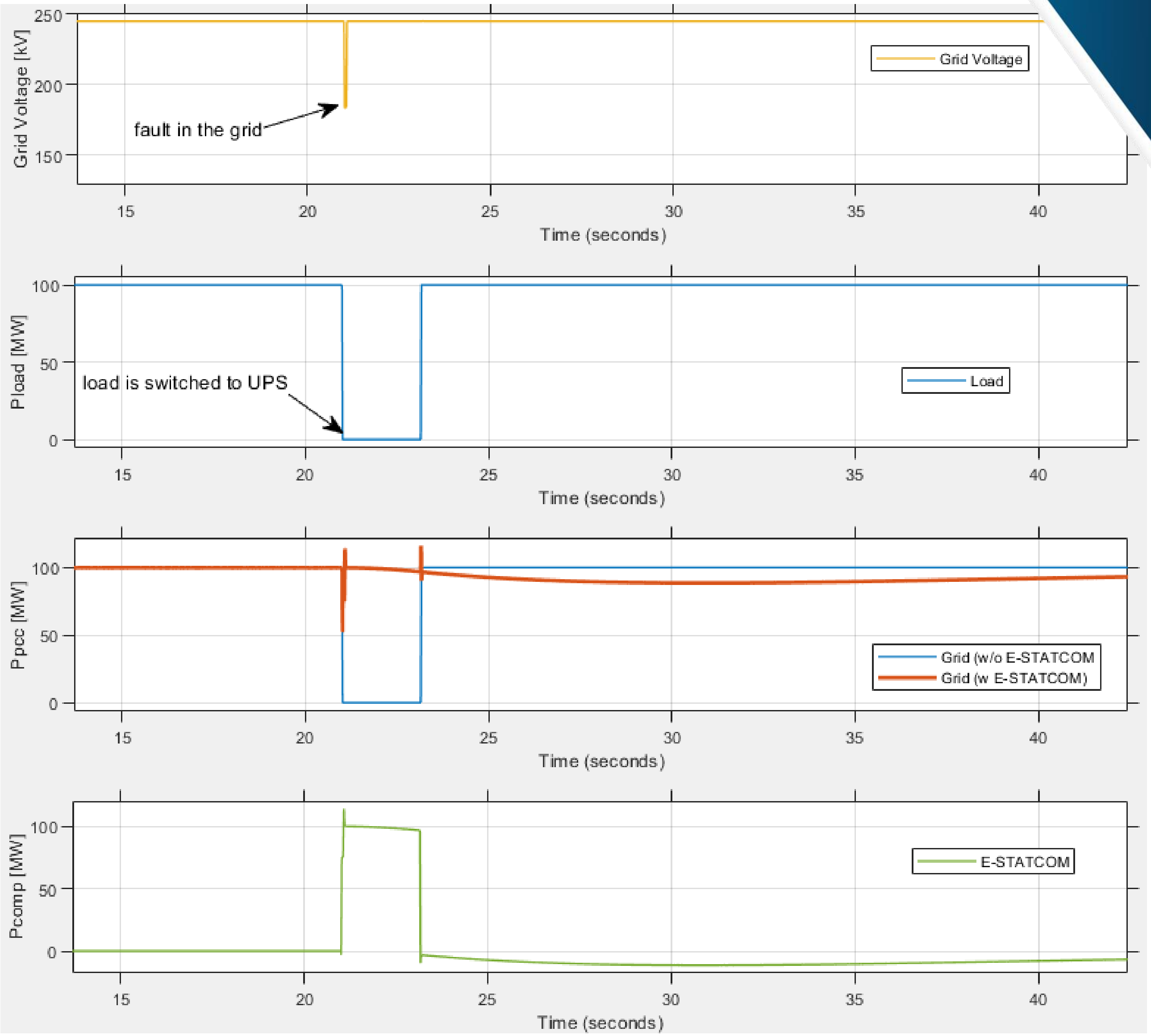
- A STATCOM (static synchronous compensator) is basically an inverter without a real power source.
  - The concept is similar to a synchronous condenser but implemented in power electronics.
- An **E**-STATCOM adds a low-energy-capacity power source to the DC bus, such as a supercapacitor bank.
  - This allows *4-quadrant* operation, meaning it can source and sink both real and reactive power.
- Supercapacitors are well-suited because of their power density, fast response, and high cycle life.



T. Engelbrecht *et al*., "STATCOM Technology Evolution for Tomorrow's Grid: E-STATCOM, STATCOM With Supercapacitor-Based Active Power Capability," in *IEEE Power and Energy Magazine*, vol. 21, no. 2, pp. 30-39, March-April 2023. [Available here].

E-STATCOMS AND VOLTAGE RIDE-THROUGH

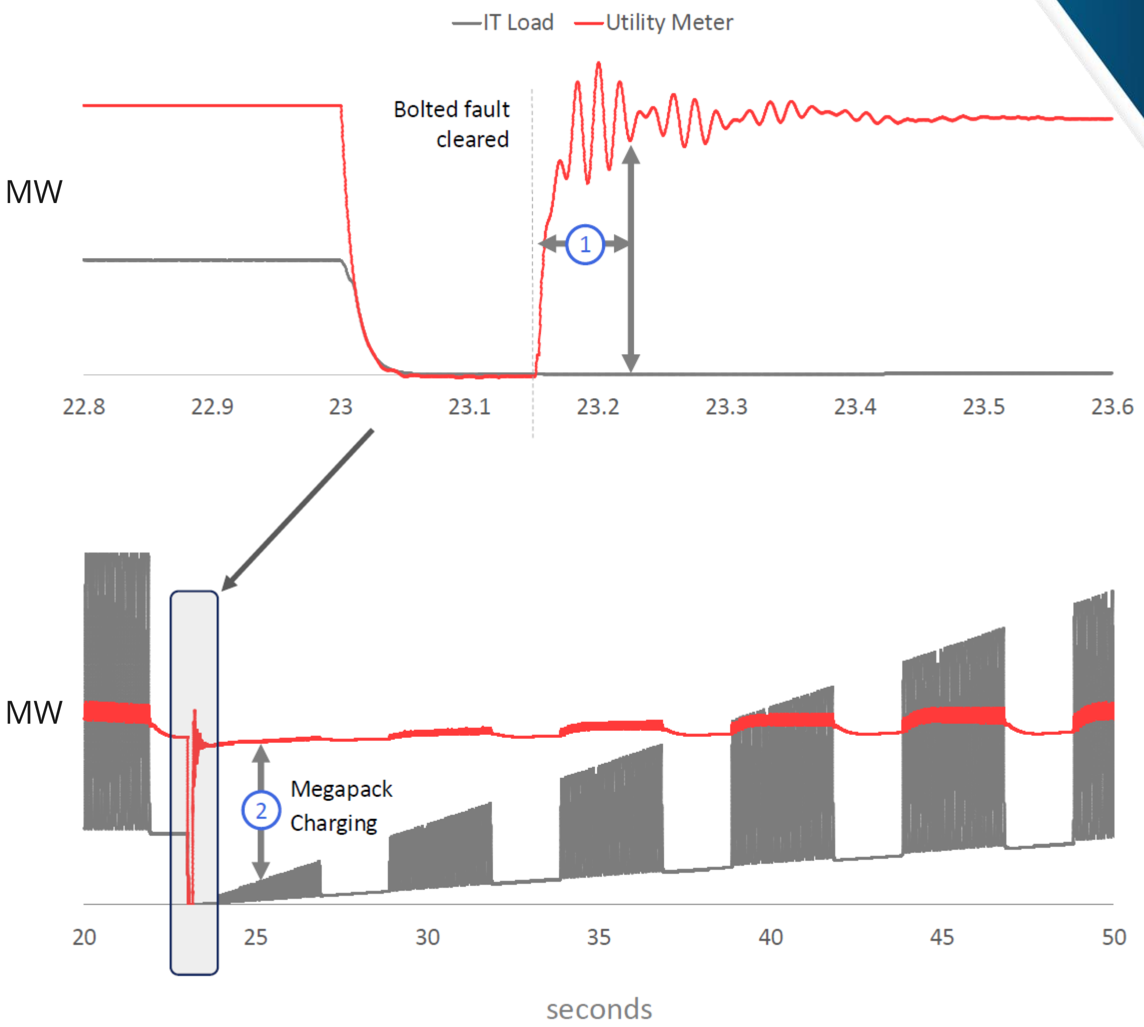
- Suppose there's a fault on the grid and the data center switches its IT load to UPS.
- The grid sees a large loss of load, the exact outcome we're trying to avoid.
- However, an E-STATCOM could be used to inject reactive power and absorb real power.
- The E-STATCOM "bridges the active power gap" while the load is served by the UPS.
- This allows the data center to protect its IT equipment without causing a disruption for the grid.



S. Kynev, "Application of E-STATCOM for AI Datacenters," presented at the ESIG Large Load Task Force, Mar. 20, 2025. [Available here](#).

CENTRALIZED BATTERY ENERGY STORAGE

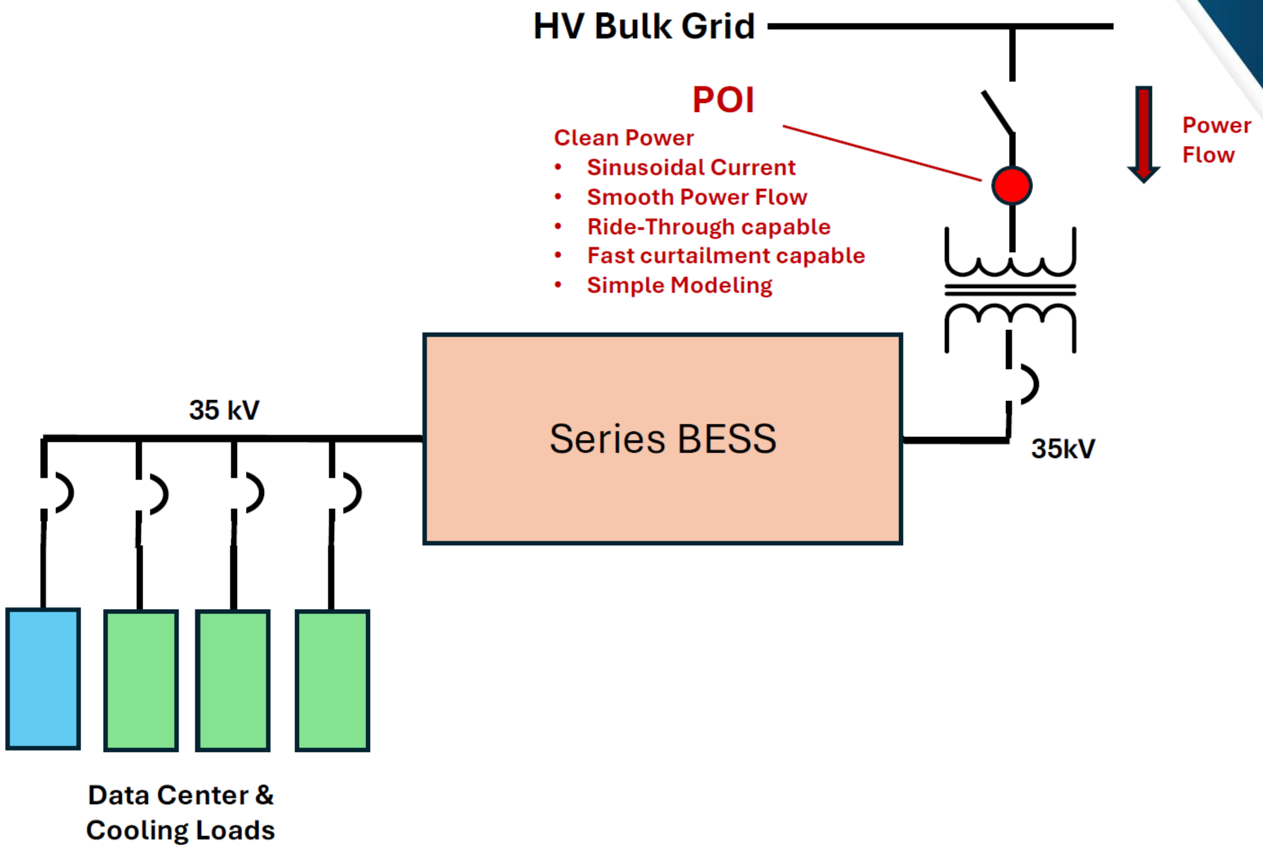
- E-STATCOMs can be great tools, but they typically can only provide active power support for several seconds.
  - What if you have a fault that takes time to recover from?
- Centralized battery energy storage (BESS) provides significant duration flexibility, commonly providing full power for 2+ hours.
  - This flexibility allows BESS to not only compensate for lost load, but also to *shape* the data center's consumption pattern.
- The trade-off is that BESS can require higher upfront investment and wear out more quickly.



Tesla Industrial Content, "Battery Storage Applications at Data Centers," presented at the ERCOT Large Load Working Group, May 2025. [Available here](#).

SERIES BATTERY ENERGY STORAGE

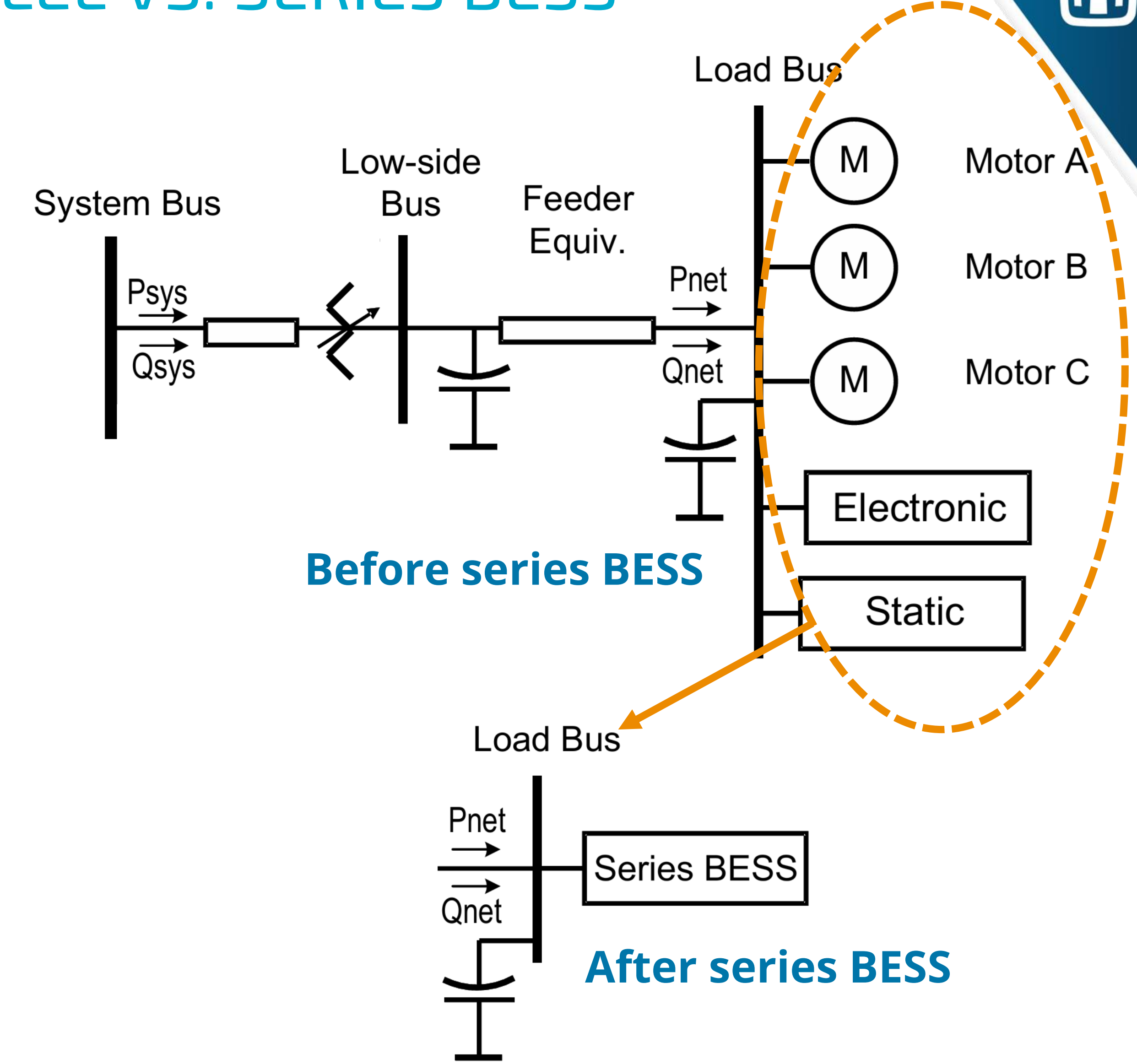
- Traditional batteries are connected in parallel with the data center load.
  - What if instead we put the entire data center behind a site-wide UPS?
- Generally, only the IT load is backed by a UPS, but this architecture can condition *all* power flowing to the facility.
  - The trade-offs are that you need a much bigger battery and the power electronics need to handle the entire site.
- This approach would require higher upfront cost than traditional BESS and incur higher conversion losses, unless cooling is bypassed.



A. McDonnell, "Series-Connected AC/DC/AC BESS for AI Data Center Grid Interconnection," presented at the ERCOT Large Load Working Group, May 21, 2026. Available here.

INTERCONNECTION STUDIES: PARALLEL VS. SERIES BESS

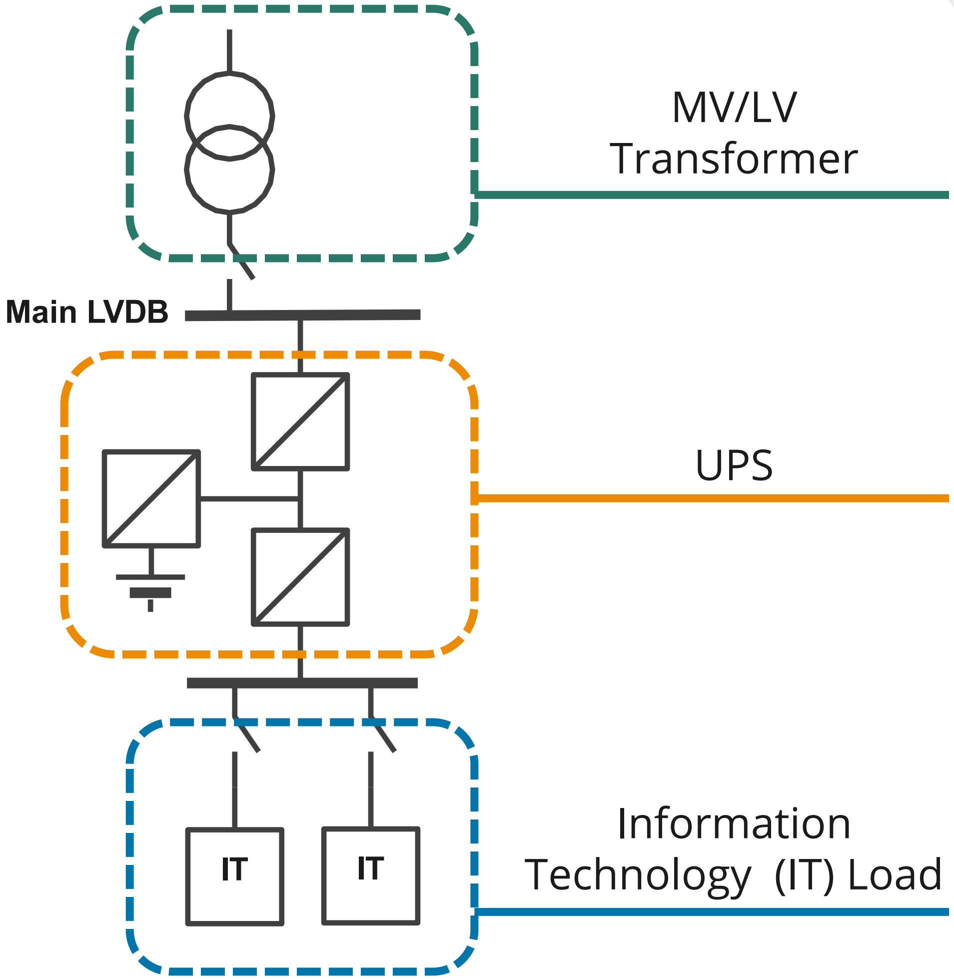
- A conventional data center presents a mix of resources at the POI, each with different fault responses and protection settings.
  - A parallel BESS adds controllability but also introduces an additional component that needs to be modeled accurately.
- A series BESS replaces this complexity with a single converter interface, reducing the grid-facing modeling burden.
  - ERCOT still requires hardware-validated EMT models with real control loops for the converter.
- A simpler facility model *does not eliminate* the need to study the full range of credible contingencies.



WECC Modeling and Validation Subcommittee, "WECC Composite Load Model Specification," Western Electricity Coordinating Council, Apr. 2021. Available here.

GRID-INTERACTIVE UPS

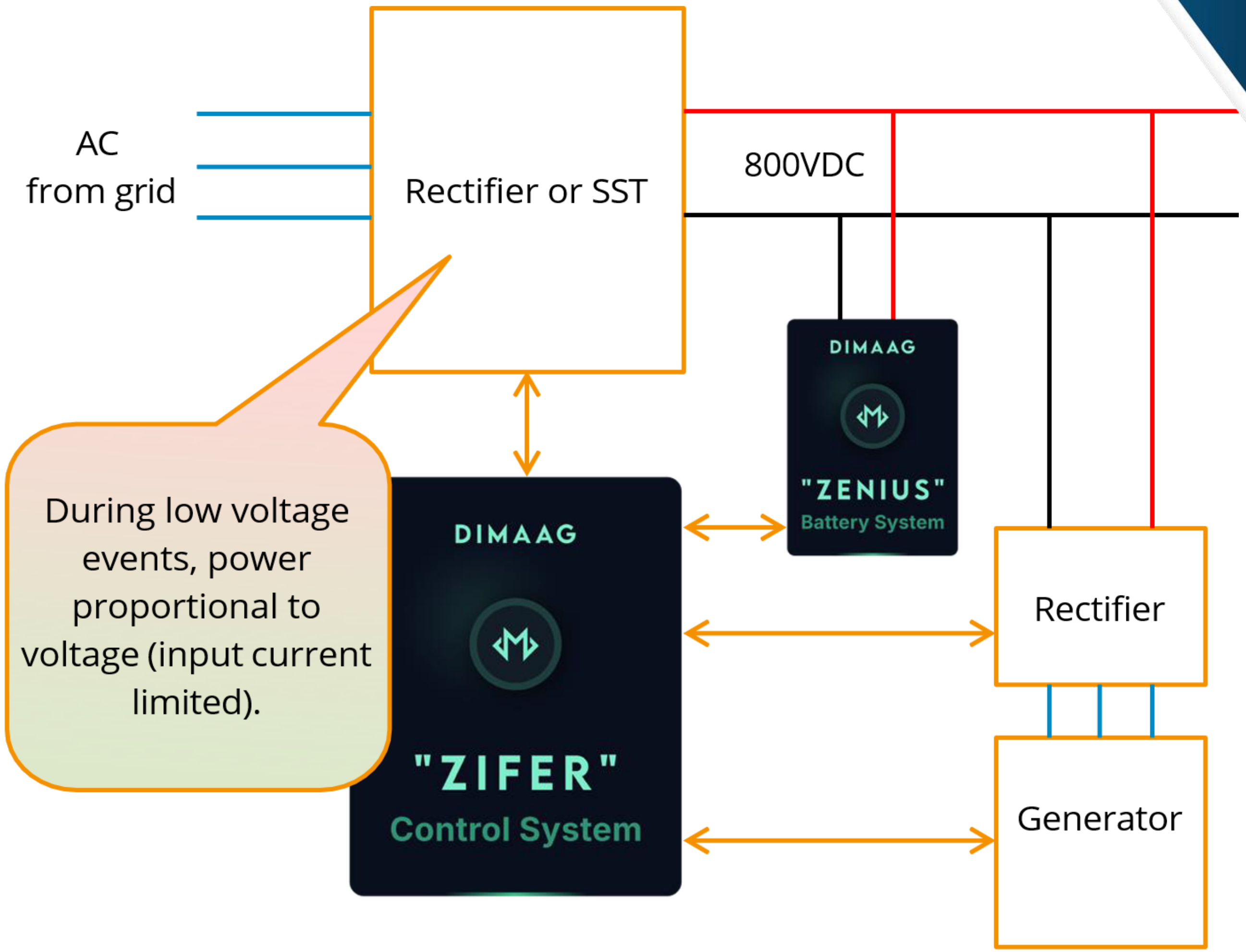
- How much voltage ride-through support can be achieved using existing UPS?
- The first feature of a *grid-interactive UPS* is a wider operating range, e.g., extending the rectifier turn off limit to -50% voltage.
  - In this range, the UPS operates in power sharing mode, drawing what it can from the grid while the battery covers the rest.
- The second feature is the ability to adjust the consumption of the UPS to recover pre-fault demand in ≤ 2 seconds.
- No additional storage is required, and the UPS continues to protect the IT load.



K. Watson, "Data Centers — A Good Grid Citizen," presented at the ERCOT Large Load Working Group, Jul. 11, 2025. [Available here](#).

INNOVATIONS IN DATA CENTER POWER DELIVERY

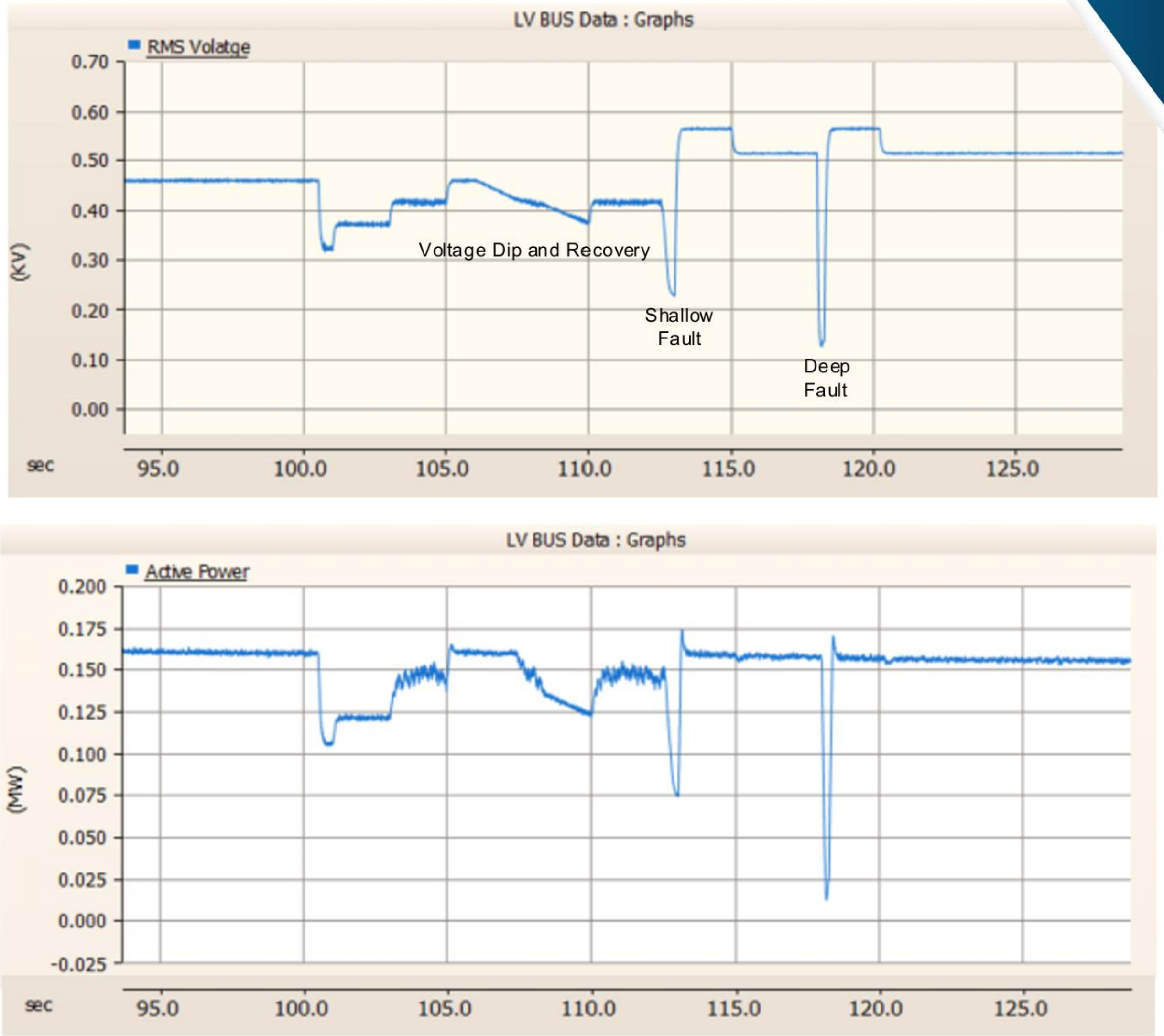
- Power delivery and distribution within data centers is rapidly evolving:
  - Distributed UPS can move storage to the rack level, improving cost and reliability.
  - Higher DC voltages can reduce conversion losses and copper reliance.
  - Solid-state transformers can enable greater controllability of power flow.
- By designing compute racks to receive 800 Vdc directly, we can “skip” one power conversion step, reducing losses.
- Instead of switching to UPS in the event of a disturbance, what if the battery was always connected to the DC bus?



I. Wright, "A New 800VDC Power Architecture," presented at the ERCOT Large Load Working Group, Apr. 24, 2026. Available here.

LOW-VOLTAGE RIDE-THROUGH WITHOUT SWITCHING

- In the other approaches we've discussed, the IT load transfers to battery backup below a certain voltage.
    - The challenge is managing what the grid sees during that transition and recovery.
- In contrast, these architectures aim to keep the load continuously connected and proportional to voltage magnitude.
- Because the IT load never switches offline, there is no delay in waiting for the energy storage to respond.



I. Wright, "A New 800VDC Power Architecture," presented at the ERCOT Large Load Working Group, Apr. 24, 2026. Available here.

TECHNOLOGY COMPARISON SUMMARY

- Centralized battery energy storage is currently the most mature technology available to support low-voltage ride-through.

	AI Load Smoothing	LVRT Support	Flexible Grid Connection	Site Model Complexity	Maturity
E-STATCOM	Partial, fast only	Depends on fault duration	No, duration limited	High	One installation to date (inertia)
Central BESS	Yes	Yes	Yes	High	Deployed at scale
Series BESS	Yes	Yes	Yes	Low, without bypass	Lab-validated, not yet deployed
Grid-Int. UPS	Depends on capacity	Yes	No, duration limited	High	First deployments underway
DC Architecture	Yes	Yes	Depends on capacity	High	Simulation and lab tests only

TECHNOLOGY COMPARISON CONTINUED

- Estimated one-time costs to achieve NOGRR 282 ride-through compliance for a 100 MW facility.

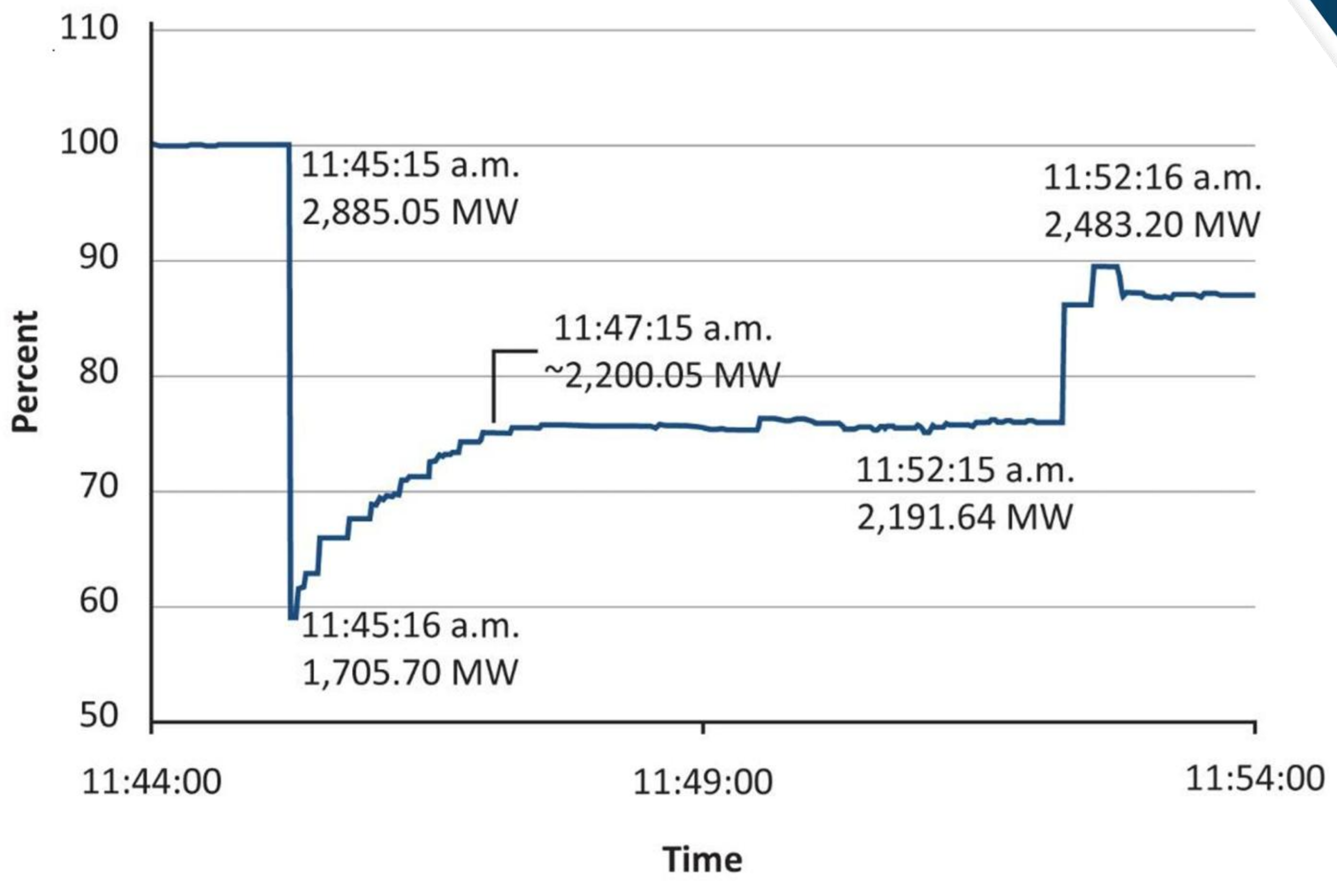
	One-time costs	Impact on facility efficiency	Retrofit possible?	Timeline for at-scale deployment
E-STATCOM	$25–50M est. for a 100 MW system	Minimal change	Yes	2–3 years (no data center installs yet)
Central BESS	$35–70M est. for a 100 MW system*	Minimal change	Yes	Available now
Series BESS	$50–90M est. for a 100 MW system*	Less efficient (conversion losses)	Yes (major equipment additions)	1–2 years (first projects commissioning)
Grid-Int. UPS	$1–15M est. for a 100 MW facility†	No change	Yes (potentially firmware only)	Available now
DC Architecture	Not separable from facility cost	More efficient (fewer conversion stages)	No (requires full redesign)	3–5 years (simulation and lab testing only)

*Cost scales with duration; 2–4 hour system.

†Leverages existing UPS infrastructure. Low end reflects firmware upgrades only; high end includes battery replacement.

FREQUENCY RIDE-THROUGH

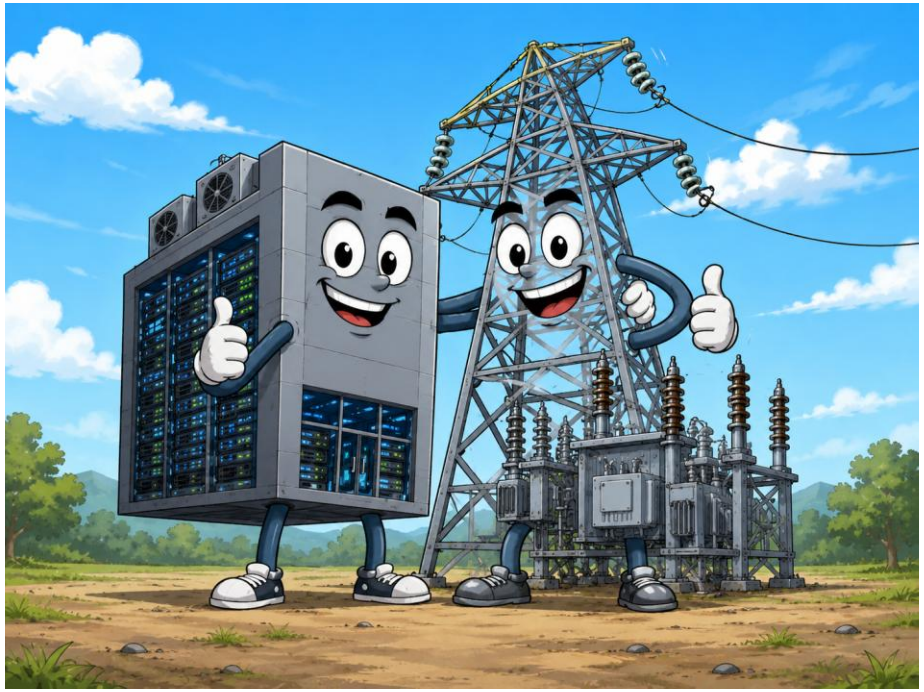
- In principle, power electronic loads can tolerate frequency deviations. A UPS or VFD does not care if the grid is at 59 Hz.
- However, the Blue Cut Fire of 2016 is evidence that expectation does not always match reality.
  - The lowest recorded frequency was 59.87 Hz, yet many inverters saw measurements below **57 Hz** due to distorted voltage waveforms.
- NOGRR 282 addresses this: protection schemes shall not trip based on instantaneous frequency measurements.



NERC, "1,200 MW Fault Induced Solar Photovoltaic Resource Interruption Disturbance Report: Southern California 8/16/2016 Event," North American Electric Reliability Corporation, Jun. 2017. Available here.

CONCLUSIONS

- Multiple technologies can achieve ride-through compliance today, each with distinct tradeoffs.
  - Centralized BESS is the most versatile. For existing facilities, UPS upgrades are the most practical.
- A simpler facility model does not reduce the number of contingencies that must be studied.
- Frequency ride-through is primarily a protection implementation problem.
- Today's facilities will be retrofitted. Tomorrow's will be designed with ride-through in mind.



QUESTIONS

- Thank you for your time.
  - We'll be happy to take any questions.

- Please feel free to reach out to:
  - Ryan Elliott, rtellio@sandia.gov
  - Matt Reno, mjreno@sandia.gov
  - Brian Pierre, bjpierr@sandia.gov

APPENDIX

GLOSSARY

Acronyms

- BESS: Battery Energy Storage System
- EMT: Electromagnetic Transient
- E-STATCOM: Enhanced Static Synchronous Compensator
- FFT: Fast Fourier Transform
- FRT: Fault Ride-Through
- IT Load: Information Technology (Computational) Load
- LCL: Large Computational Load
- LVRT: Low Voltage Ride-Through
- MV: Medium Voltage
- PFAPR: Post-Fault Active Power Recovery
- POI: Point of Interconnection
- SST: Solid-State Transformer
- STATCOM: Static Synchronous Compensator
- UFLS: Under-frequency Load Shedding
- UPS: Uninterruptible Power Supply
- UV: Under-voltage
- VFD: Variable Frequency Drive

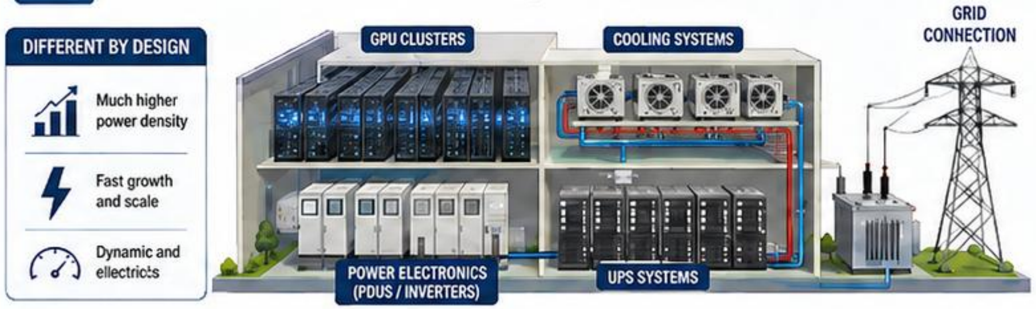
Key terms

- Ride-through: Remaining connected to the grid during a voltage or frequency disturbance
- Power sharing mode: UPS draws partial power from the grid while the battery covers the rest
- Double conversion: Power passes through two conversion stages (AC→DC→AC), fully isolating the load
- Shunt: Connected in parallel with the load
- Series: Connected between the grid and the load

AI Data Centers: Grid Challenges and Opportunities

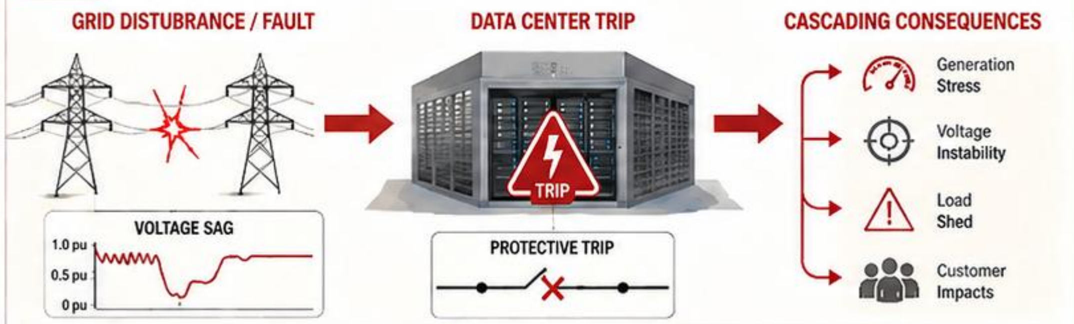
How AI-driven loads are changing reliability, interconnection, and controllability

1. The New Load Reality



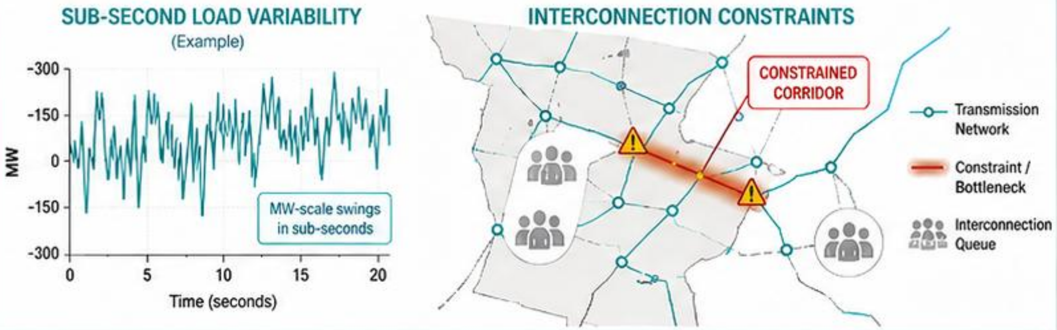
- High power density and rapid growth
- Power-electronic, UPS, and inverter-rich load
- Different operating behavior than traditional industrial load

2. Reliability Risks



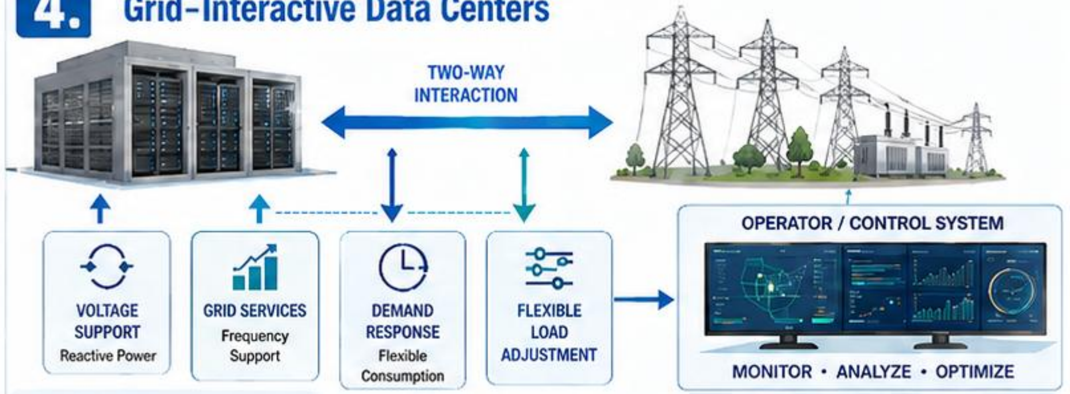
- Large electronic loads may trip during grid faults
- Failure to recover can create cascading consequences
- ERCOT NOGRR 282 drives new ride-through requirements

3. AI Training Load Variability & Interconnection Constraints



- Sub-second MW-scale load swings
- Synchronized GPU workloads create volatile demand
- Transmission constraints limit where and how fast load can interconnect

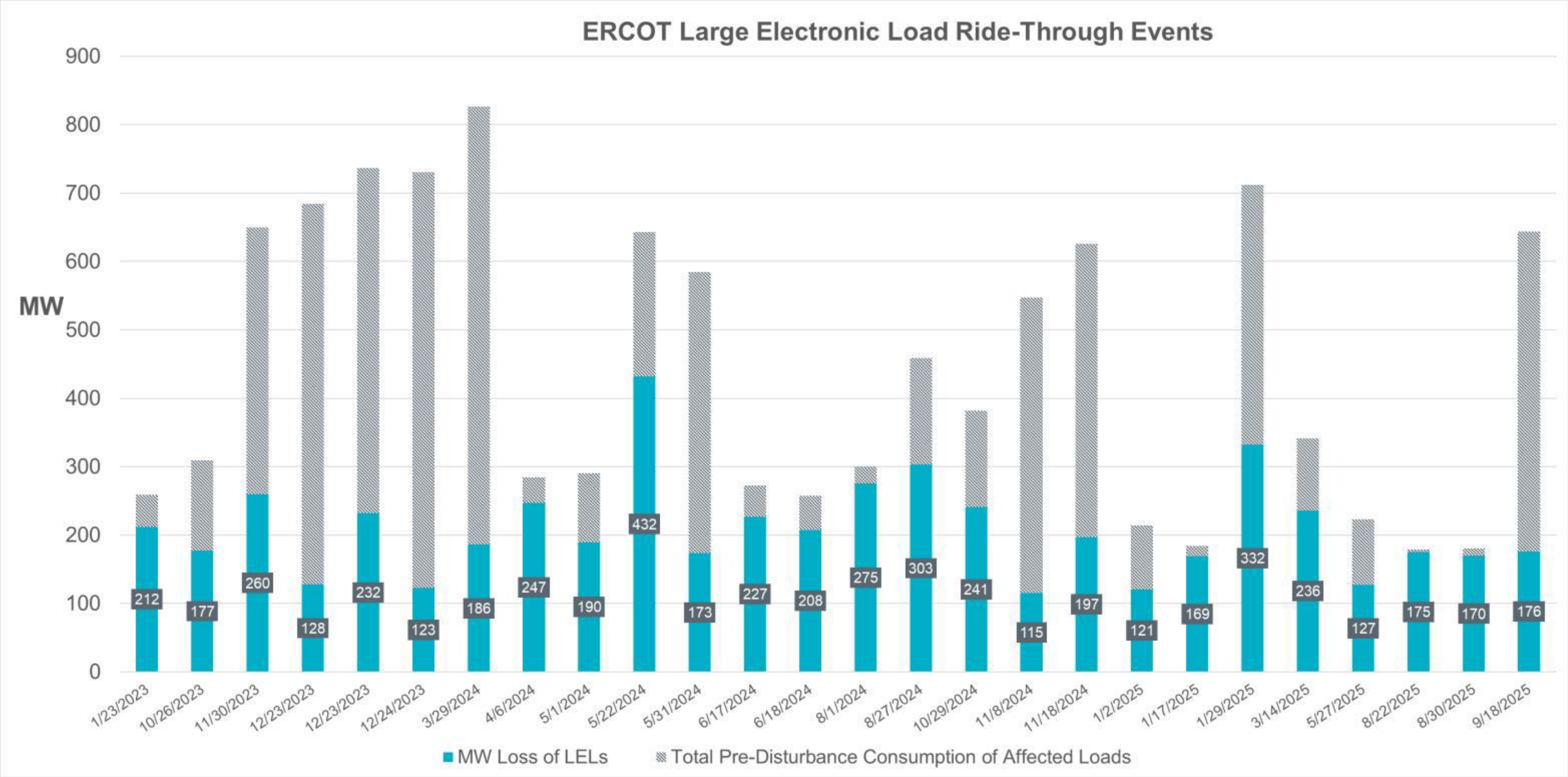
4. Grid-Interactive Data Centers



- Reactive power support
- Demand response and flexible consumption
- Load can adjust to grid conditions in real time

THE CASE FOR RIDE-THROUGH REQUIREMENTS

- Between 2023–2025, ERCOT identified 26 events in which large computational loads tripped during routine voltage disturbances that the grid was designed to handle.
- NOGRR 282 establishes ride-through requirements to prevent large computational loads from amplifying routine disturbances into system-wide events.



Links to previous ERCOT presentations:

- June 13 Large Load Workshop
- July 11 LLWG (ERCOT LEL Ride Through Criteria)
- Sept. 19 LLWG (ERCOT study update presentations)
- Oct. 24 LLWG (ERCOT study update presentation)

J. Billo, "Large Electronic Load Ride-Through Requirements," presented at the ERCOT Board of Directors Meeting, Dec. 8–9, 2025. Available here.

NOGRR 282 REQUIREMENTS AT A GLANCE

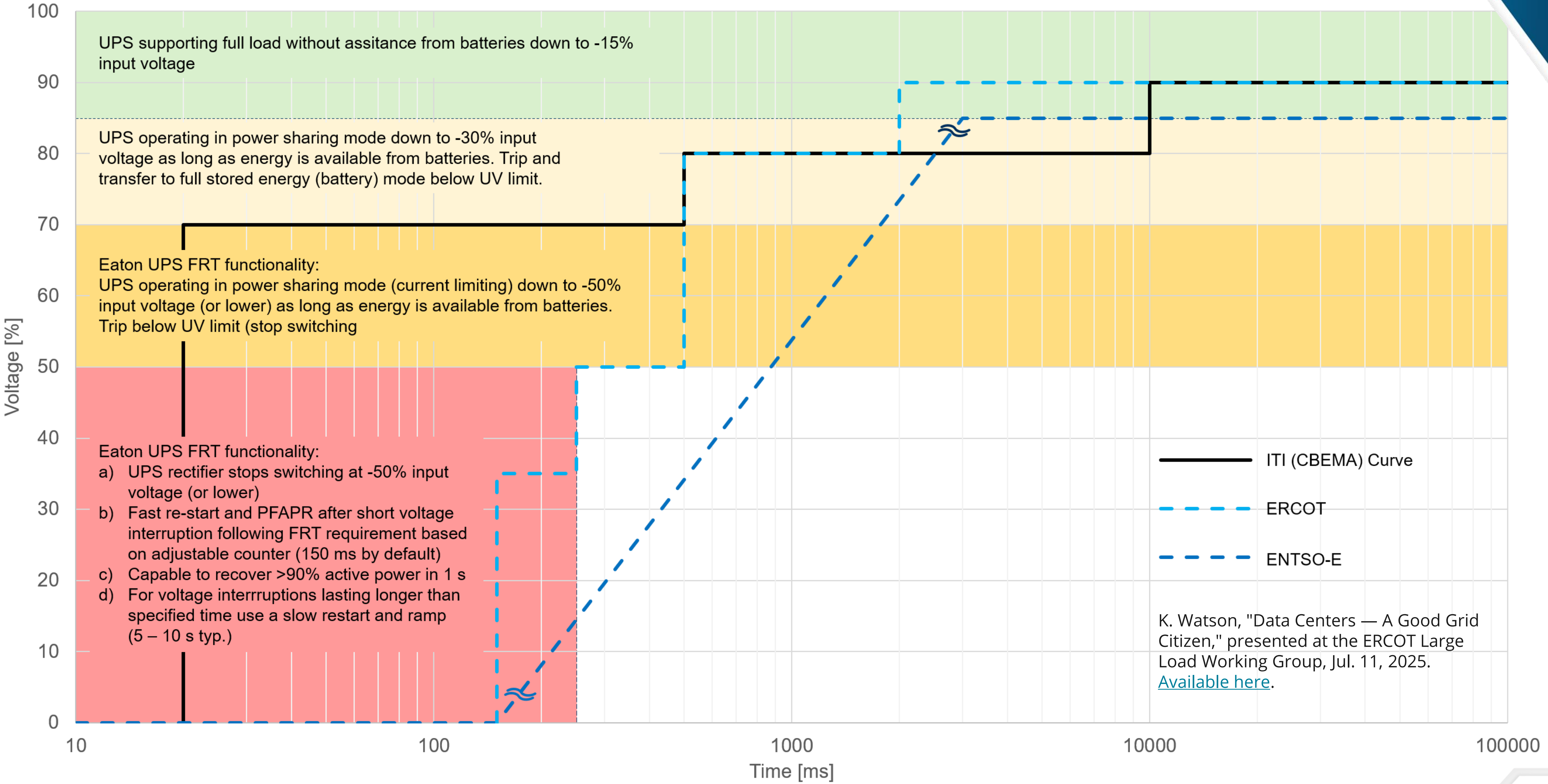
- **Voltage:** Ride through all voltages ≤ 1.20 pu for the specified duration; return to 90% of pre-fault demand within 2 seconds.
- **Frequency:** Remain connected between 57.5–63.0 Hz; maintain consumption within 10% of pre-disturbance level.

Root-Mean-Square Voltage (p.u. of nominal)	Minimum Ride-Through Time (seconds)
$V > 1.20$	May ride-through or trip
$1.10 < V \le 1.20$	1.0
$0.90 \le V \le 1.10$	Continuous
$0.80 \le V < 0.90$	2.0
$0.50 \le V < 0.80$	0.5
$0.35 \le V < 0.50$	0.25
$V < 0.35$	0.15

Frequency (f) in (Hz)	Minimum Ride-Through Time (seconds)
$f > 63.0$	May ride-through or trip
$61.2 < f \le 63.0$	299
$58.8 \le f \le 61.2$	continuous
$57.5 \le f < 58.8$	299
$f < 57.5$	May ride-through or trip

ERCOT, "NOGRR 282: Board Priority — Large Computational Load Ride-Through Requirements," approved by the Public Utility Commission of Texas, Jul. 9, 2026, effective Aug. 1, 2026. Available here.

GRID-INTERACTIVE UPS: OPERATING REGIONS



SPEED TO POWER COMPARISON TABLE

Characteristic	Grid-Connected Inflexible	Grid-Connected Flexible	Bridge to Grid (Off-Grid Temporarily)	Islanded (Off-Grid Permanently)
Relative Data Center Benefits				
Speed to Power	Worse	Average	Best	Better
Reliability of Supply	Best	Best	Average	Worse
Diversity of Supply	Best	Best	Marginal	Marginal
Data Center Costs	Average	Better	Worse	Marginal
Relative Grid/Societal Benefits				
Grid Infrastructure Costs	Average	Best	Average	Better
Grid Reliability/Services	Better	Best	Better	Better
System Emissions	Average	Better	Marginal	Average

Rating: Worse, Marginal, Average, Better, Best

EPRI, "Reconciling the Value of Grid Interconnection and Speed to Power: Strategies for Powering Data Centers in the AI Era," Electric Power Research Institute, Nov. 2025. Available here.

Grid Impacts of Voltage & Frequency Ride-Through Requirements for Data Centers

What parts of the grid are affected when large data centers must remain connected during disturbances?

1 Protection & Transfer Controls

Relays, UPS transfer logic, and automatic transfer schemes must coordinate with ride-through settings.

2 Voltage Control Equipment

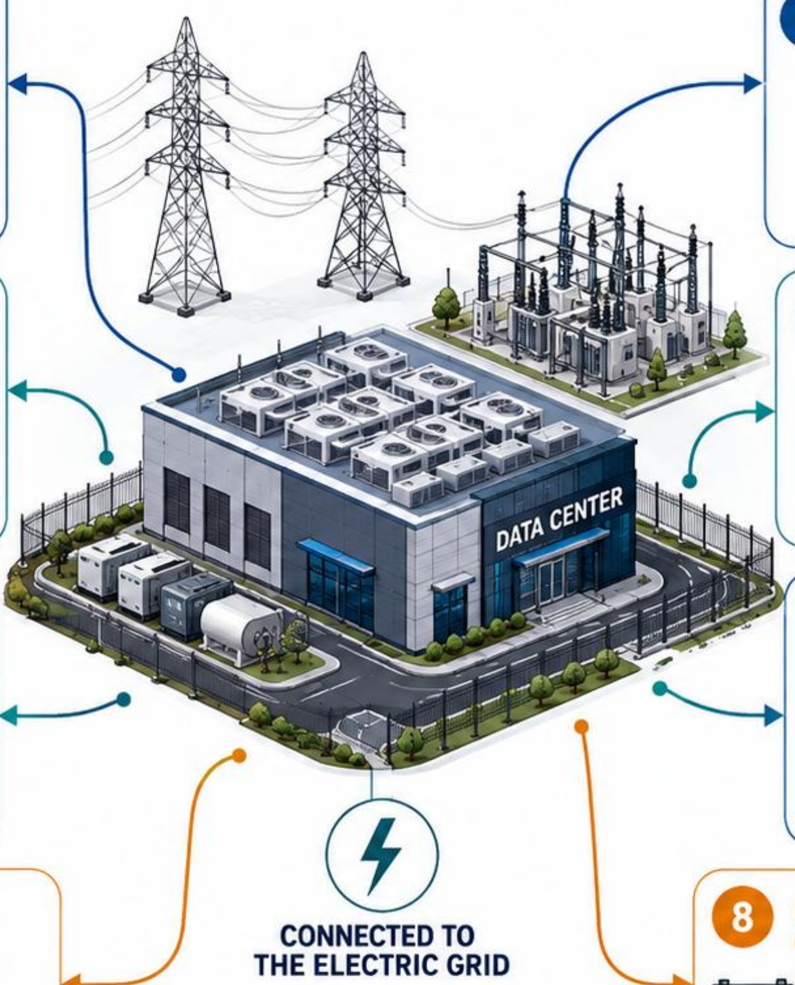
SVCs, STATCOMs, capacitor banks, tap changers, and reactive power controls must support voltage recovery.

3 Generators & Frequency Response

Large load loss or recovery affects governors, AGC, reserves, and system frequency.

4 UFLS / UVLS & Load Shedding

Ride-through settings must be coordinated with emergency load shedding programs.



5 Transmission Planning & Interconnection

Studies must model fault response, recovery, reconnection, and load ramps.

6 Lines, Substations & Transformers

Post-fault loading, recovery current, and voltage support needs can drive upgrades.

7 Monitoring & Operator Visibility

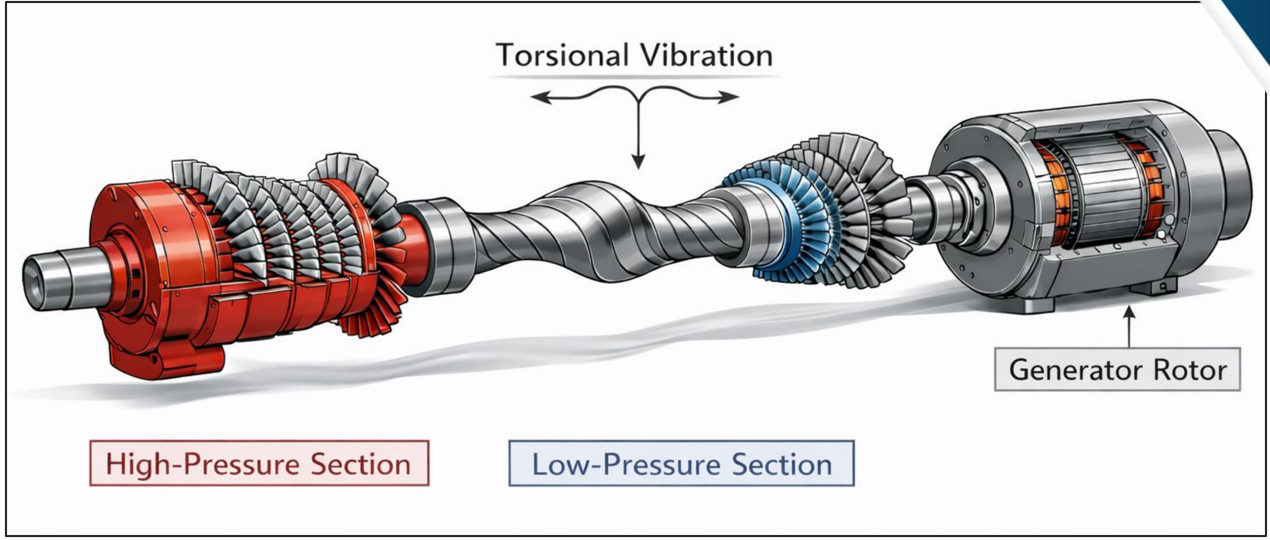
SCADA, PMUs, telemetry, and event analysis are needed to see how the facility responds.

8 Blackstart, Restoration & On-Site Resources

Pickup sequencing, batteries, and backup generation must be coordinated with restoration.

DATA CENTERS AND SUBSYNCHRONOUS OSCILLATION

- Subsynchronous oscillations (SSO) are power variations below 60 Hz that can excite torsional resonances in generator shafts.
- AI training workloads produce periodic power swings at frequencies of concern.
- Converter control interactions can also produce oscillations, particularly when DC bus voltages are poorly regulated.
- Utilities are beginning to set limits on oscillation energy by frequency band.
- Monitoring subsynchronous oscillations requires high-sample-rate sensors at the point of interconnection (see PNNL-39191).

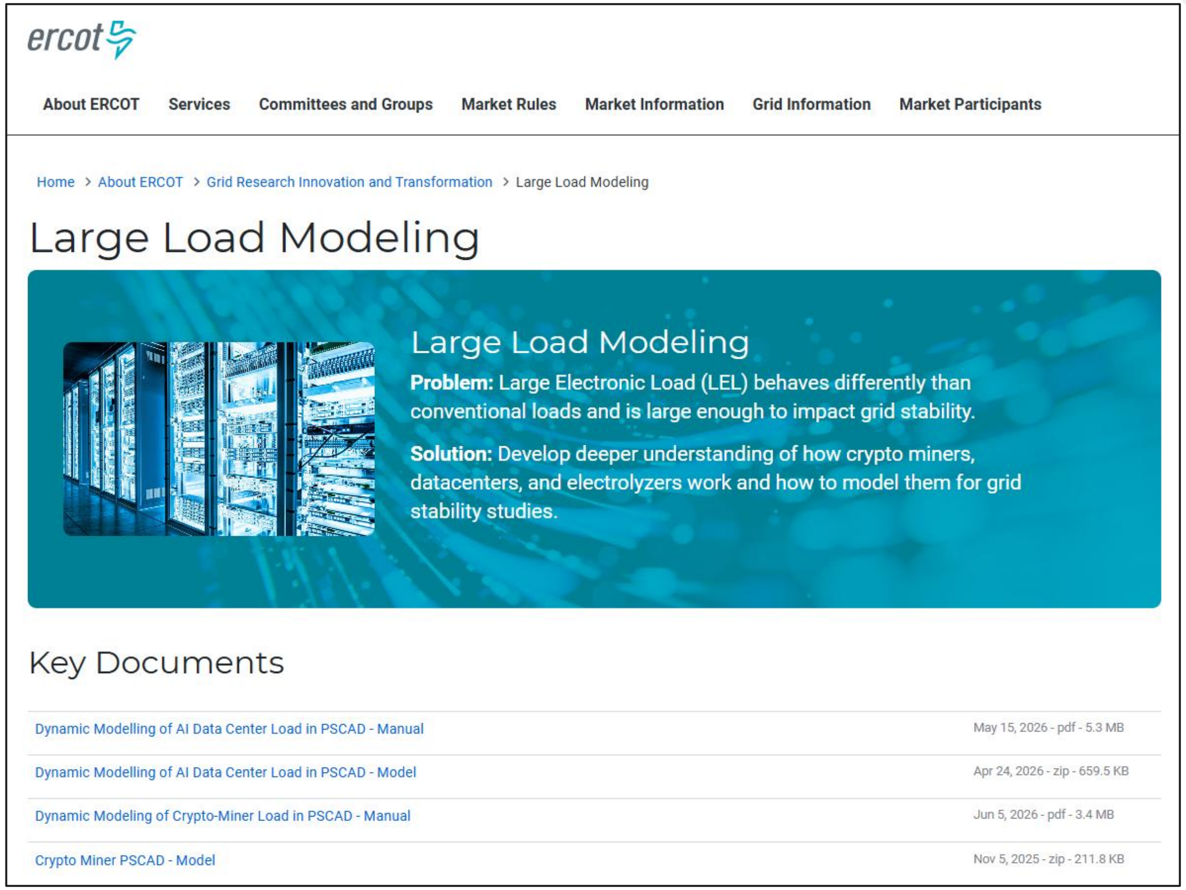


Frequency Range	Oscillation Type	Limit (per 0.1 Hz FFT bin)
0.1–0.8 Hz	Bulk-system / inter-area modes	≤ 10 MW
0.8–5.0 Hz	Local / intra-plant / control modes	≤ 10 MW
5.0–55.0 Hz	Subsynchronous torsional modes	≤ 2.5 MW

Southern Company, "Technical Requirements for Transmission Connected Large Loads - v1.4," May 1, 2026. Available here.

LARGE LOAD MODELING

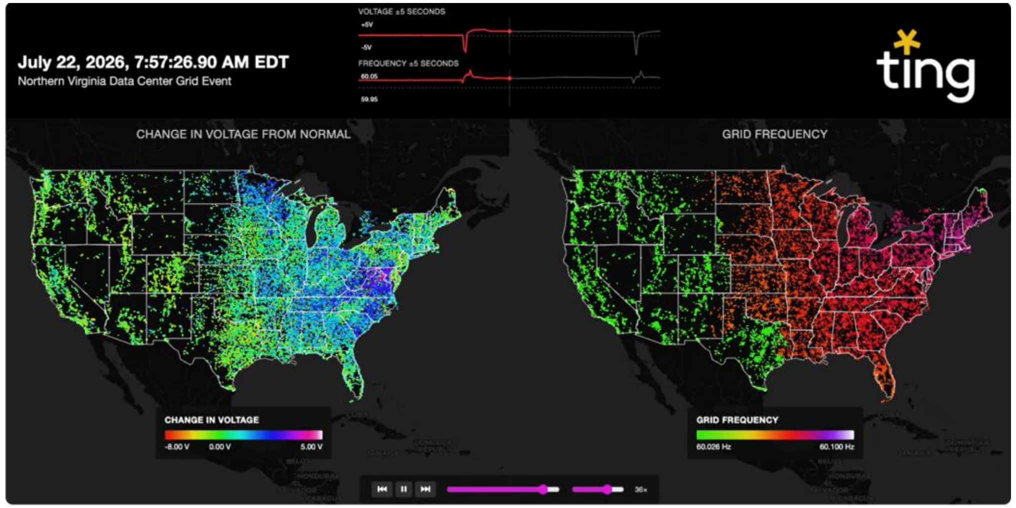
- There is a need for new models to represent power electronic-interfaced large loads, both in positive-sequence phasor domain (PSPD) and electromagnetic transient (EMT) simulations.
- Models:
  - https://www.ercot.com/about/grit/large-load-modeling
  - https://github.com/HewlettPackard/sustain-cluster
  - https://ieee-dataport.org/open-access/data-center-model-library-electromagnetic-transient-analysis-pscad
- Datasets from data centers
  - https://github.com/MIT-AI-Accelerator/MIT-Supercloud-Dataset
  - https://data.nlr.gov/submissions/312
  - https://github.com/Ahmed-Elsayed95/High-resolution-AI-Data-Center-Training-Workloads-Dataset/



ERCOT dynamic models of AI data center load and crypto-miner load. Available here.

ADDITIONAL RESOURCES

- NERC Large Loads Action Plan, Large Loads Working Group, and Load Modeling Working Group
- ERCOT Large Load Working Group (LLWG) – monthly meetings with presentations available online
- ERCOT Large Load Integration
- CAISO Large Loads Stakeholder Initiative
- MISO Large Load Additions, Working Group, and Workshops
- ESIG Large Loads Working Group – technical reports publicly available
  - ESIG Flexible Interconnections for Large Loads Workshop (6/17/26) – presentations available online
  - ESIG/NLR Large Load Modeling, Testing and Interconnection Requirements Workshop (6/16/26) – presentations available online
- Large Load Literature Review (LBNL)
- EPRI Large Load Research, Data Center Flexibility, and Speed to Power
- Large Load References (Eric Meier)



Video of July 2026 Northern Virginia Data Center Event - Effects on Voltage & Grid Frequency. Available here.