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ENERGY SOLUTIONS

ESIG Spring Workshop
March 19, 2026

CONSIDERATION FOR EMT MODELING OF DATA CENTER LOADS

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AGENDA

1. Data center load characteristics
2. Electronic load modeling
3. Model Validation
4. Conclusion

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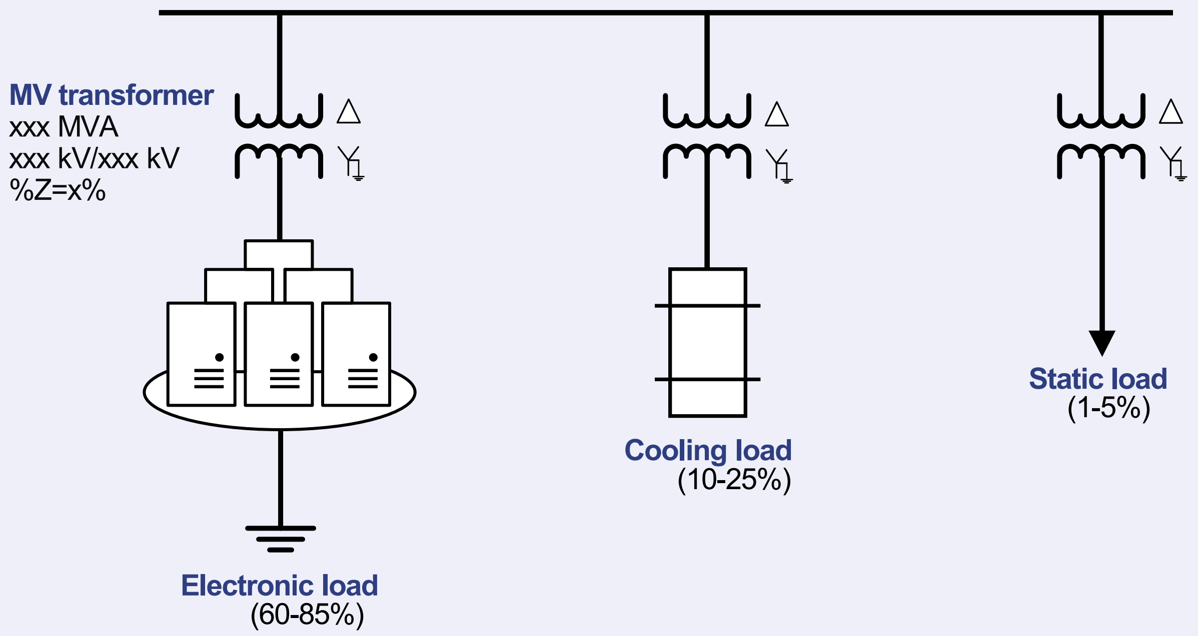
DATA CENTER LOAD CHARACTERISTICS

AGGREGATE COMPOSITE LOAD MODEL

The load profile is heavily dominated by electronic loads, with cooling representing a secondary share, reinforcing the importance of accurately modeling electronic load behavior in system studies.

MAJOR CATEGORY	SUB-CATEGORY/ EXAMPLE	% OF TOTAL LOAD
Electronic loads	• Power supply unit (PSU) • Uninterruptible power supply (UPS)	60–85%
Cooling loads (Motor loads)	• Directly connected motors • VFD connected motors	10–25%
Auxiliary/ static loads	Constant-impedance loads (lighting, small services)	1–5%

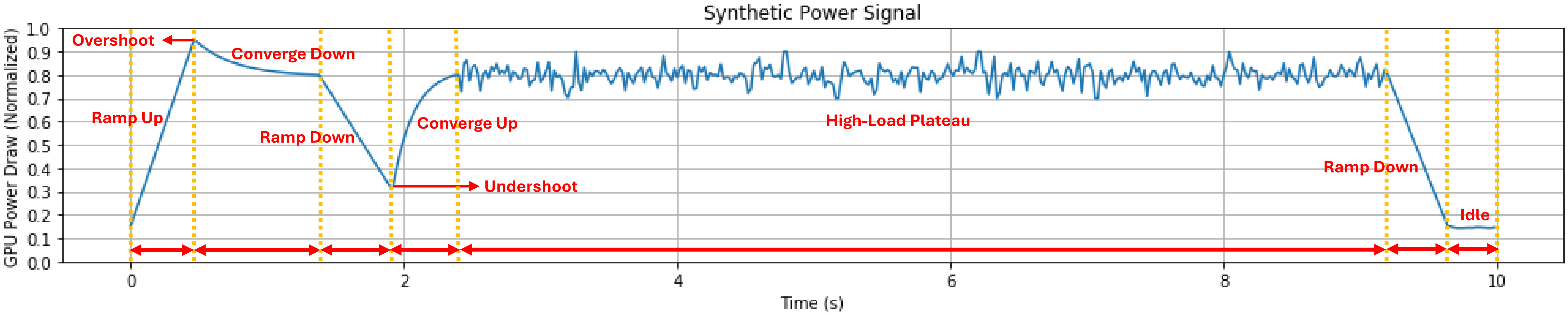


AI LOAD PROFILES

AI loads are highly dynamic and nonlinear, exhibiting rapid ramps and significant fluctuations that can impact system stability and power quality.

Key characteristics of AI loads:

- Overshoot/Undershoot
- Ramp up/down
- Duty Cycle
- Convergence up-down
- Frequency Content



A Typical Operating Cycle of the AI Load

AI LOAD CHALLENGES

The AI load can also introduce several challenges to the electric grid:

Load-side impacts:

- Low-voltage generator oscillation
- Reduced lifetime of UPS and battery backup units
- Power quality challenges (harmonics & flicker)
- Strain on distribution infrastructure and sensitive IT equipment
- Higher cooling demand
- Reduced energy efficiency (PUE)

Grid-side impacts:

- Voltage flicker and TOV
- Frequency variation and reduced damping of interarea oscillations
- Sub-synchronous oscillations, affecting synchronous generators (SSR) and inverter-based resources (SSTI/SSCI)
- Ride-through limitation
- Harmonics from HF switching
- Thermal stress on primary power equipment

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ELECTRONIC LOAD MODELING

ELECTRONIC LOADS

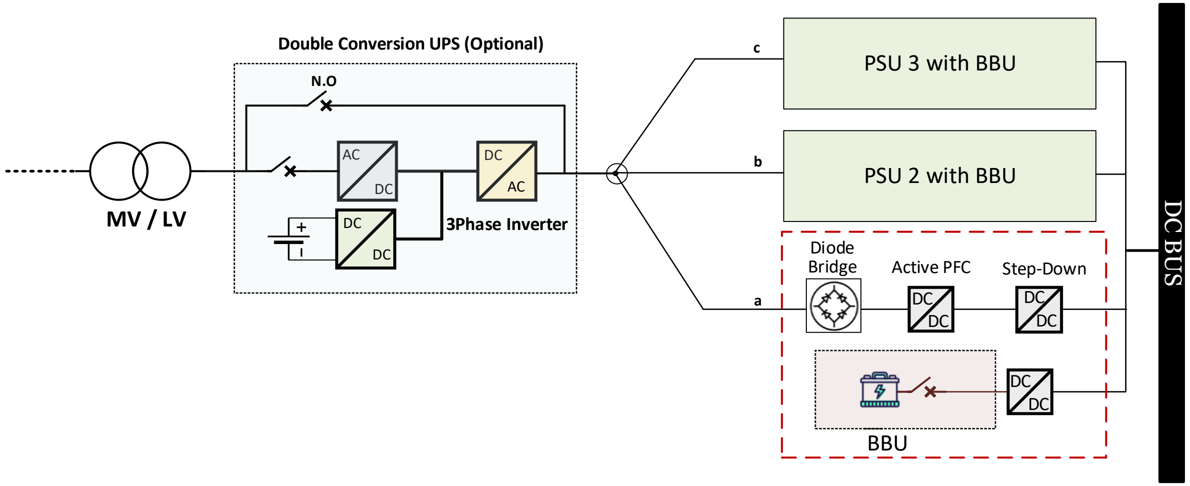
High-quality EMT studies of data center electronic loads require explicit modeling of constant-power behavior, current control limits, and DC-link dynamics, depending on the system study.

Modeling requirements for EMT studies

- Single-phase behavior of PSUs
- Control and protection functions (VRT, FRT, current limits)
- Constant-power load (CPL) behavior of electronic loads
- Operating modes as a function of voltage
- Representation of AI load variability (custom AI load profile).

Additional requirements (for certain studies)

- Harmonic contents of electronic loads
- All power conversion stages and associated DC links
- BBU models and transition between PSU and BBU
- Detailed DC bus dynamics and harmonic oscillations.



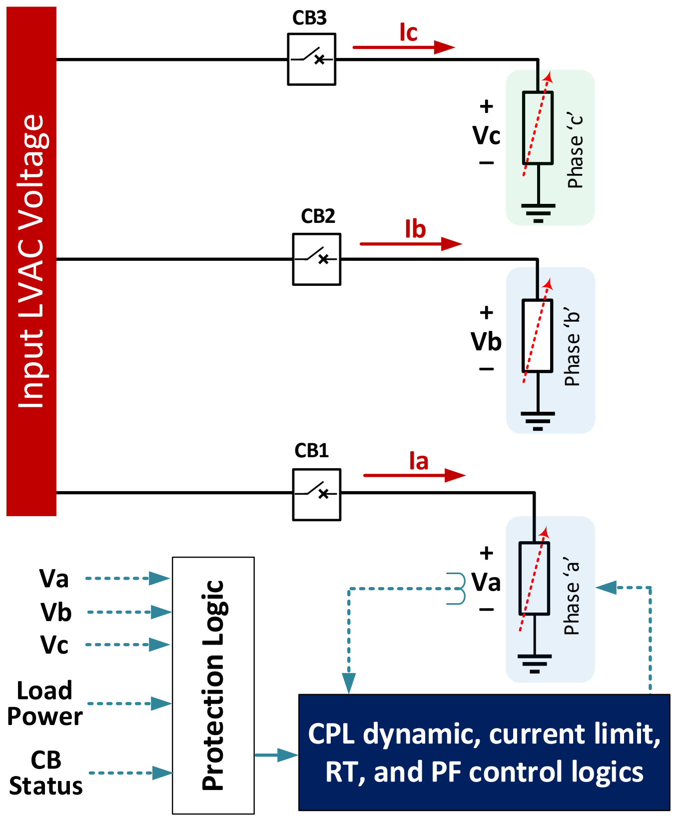
Building blocks of the electronic load models

AVERAGE MODEL

The average model provides a configurable, phase-level representation of constant-power behavior, protection functions, and load variability, enabling scalable system-level studies without full switching details.

In this model:

- PSUs are modeled as three independently controlled RLC loads.
- Load can track active and reactive power setpoints under varying grid voltage conditions per phase (i.e., 3 x single-phase CPL representation).
- DC-side current limits and control dynamics are represented.
- VRT/FRT functionality is represented.
- AI load power fluctuation can be represented.



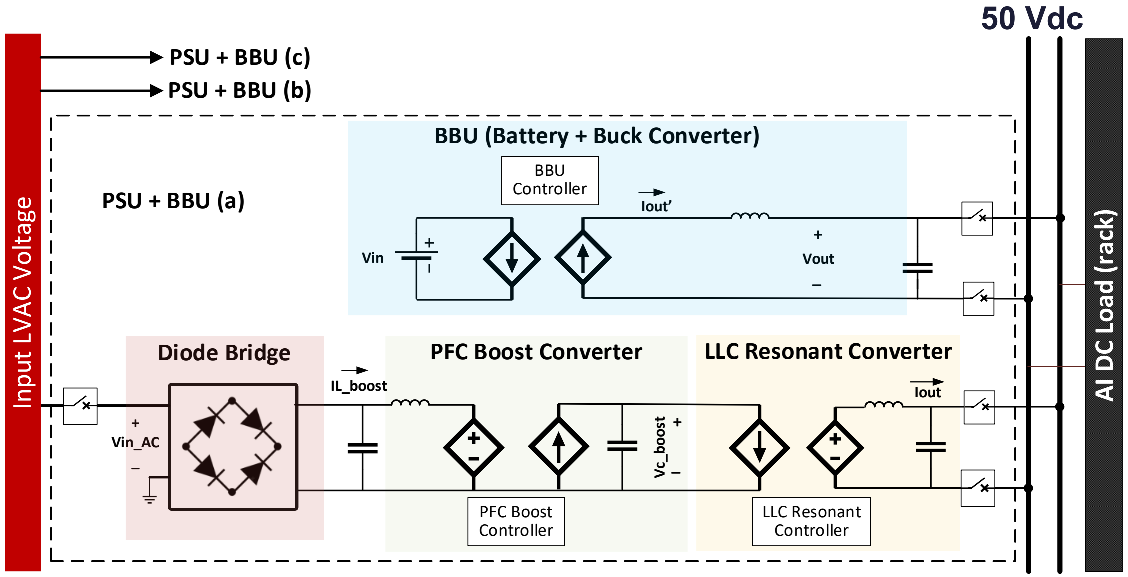
FEATURES
Adjustable VRT/FRT settings
Adjustable AI load profile
Adjustable sizing and scalability
Adjustable recovery

AVERAGE SWITCHING MODEL

The average switching model captures converter topology, control structure, and DC bus dynamics with greater fidelity than the average model, enabling more accurate assessment of fast transients and control interactions.

In this model:

- PSUs are represented as three single-phase power electronic units.
- All the power conversion stages are modeled:
  - Diode bridge (detailed switching model)
  - PFC boost converter (average switching model with full control)
  - LLC resonant converter (average switching model with simplified control).
  - BBU and associated dc/dc controls (average switching model).
- VRT/FRT functionality is represented.
- AI load fluctuation can be represented as DC loads on the 50 Vdc bus.



FEATURES

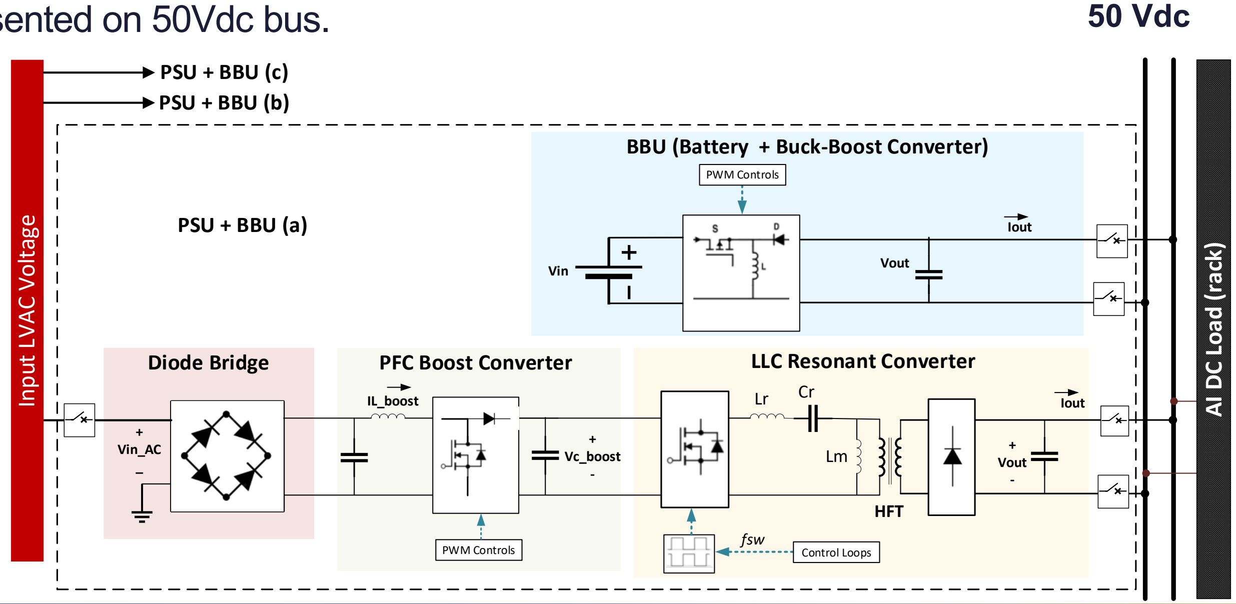
Adjustable VRT/FRT settings
Adjustable AI load profile
Adjustable sizing and scalability
Adjustable recovery

DETAILED SWITCHING MODEL

The detailed switching model provides device-level fidelity of converter dynamics and control interactions, enabling high-confidence analysis of fast transients, harmonic behavior, and control-driven instability mechanisms.

In this model:

- PSUs are represented as three single-phase power electronic units.
- All the power conversion stages are modeled, including:
  - Diode bridge (actual switching)
  - PFC boost converter (switching model with full control structure)
  - LLC resonant converter (switching model with detailed control).
  - BBU and associated dc/dc converters (average switching model) are represented
- VRT/FRT functionality is represented.
- AI load fluctuation can be represented on 50Vdc bus.



FEATURES

Adjustable VRT/FRT settings
Adjustable AI load profile
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Adjustable recovery

SUMMARY OF DIFFERENT MODELING APPROACH

Model selection requires balancing fidelity, scalability, and computational burden: the average model supports system-level studies efficiently, while detailed switching models provide device-level accuracy at significantly higher computational cost.

CAPABILITY	AVERAGE MODEL	AVERAGE SWITCHING MODEL	DETAILED SWITCHING MODEL
Primary use case	Bulk system studies (multiple substations, large-scale grid): dynamic, SSO, and fault studies	Plant-level studies (few buses away): detailed dynamics and SSO	Device-level converter validation; power quality
Switching detail	None	Averaged switching	Full device-level switching
Harmonics	Not captured	Major frequency components	Full harmonic spectrum
DC-side dynamics	Not modeled	DC bus dynamics	Full DC ripple and switching detail
Scalability	★★★★	★★★☆	★☆☆☆
1-min simulation time	~3 minutes	~12 minutes (single plant)	>3 hours (single plant)

MODEL VALIDATION

AN END-TO-END APPROACH FOR DATA CENTER LOAD MODELING

An integrated modeling and verification workflow enables accurate model calibration and greater technical confidence, reducing deployment uncertainty.

Data center modeling

- **Develop** control-focused models.
- **Simulate** AI load dynamics, grid interactions, and disturbances.

+ Lab testing

- **Perform** physical lab testing and analyze HIL results.
- **Verify** protection, control, and transient performance before implementation.

→ Verified and tuned data center model

- **Calibrate** models using HIL test results.
- **Develop** model validation reports.
- **Reduce** commissioning risk

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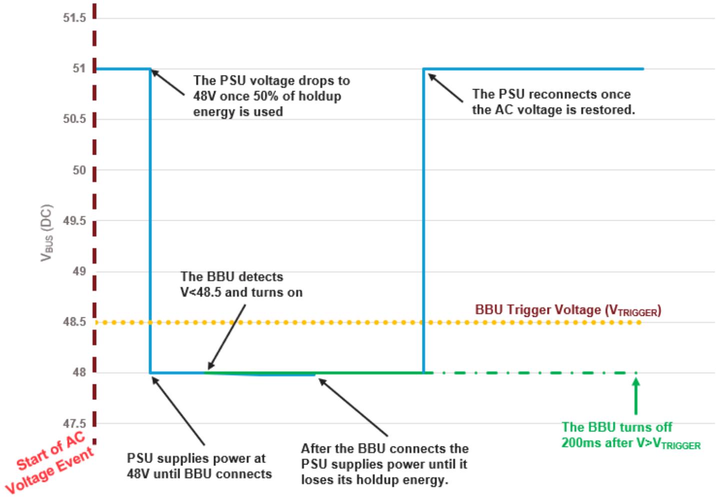
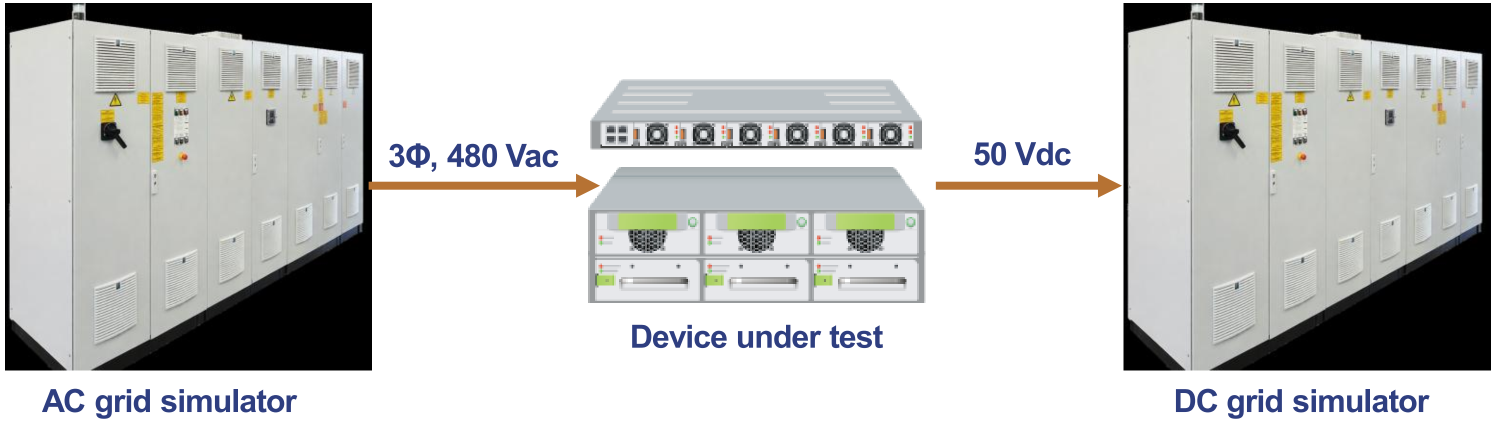
EXAMPLE HIL TESTING

Objective: Evaluate unit performance and develop a validated PSCAD model of PSUs.

- Different PSUs were tested to evaluate their performance and to develop and validate a PSCAD model.
- Testing focused on dynamic behavior and control response:
  - VRT/FRT characteristics.
  - BBU coordination during power outage events.
  - Response to fluctuating loads.

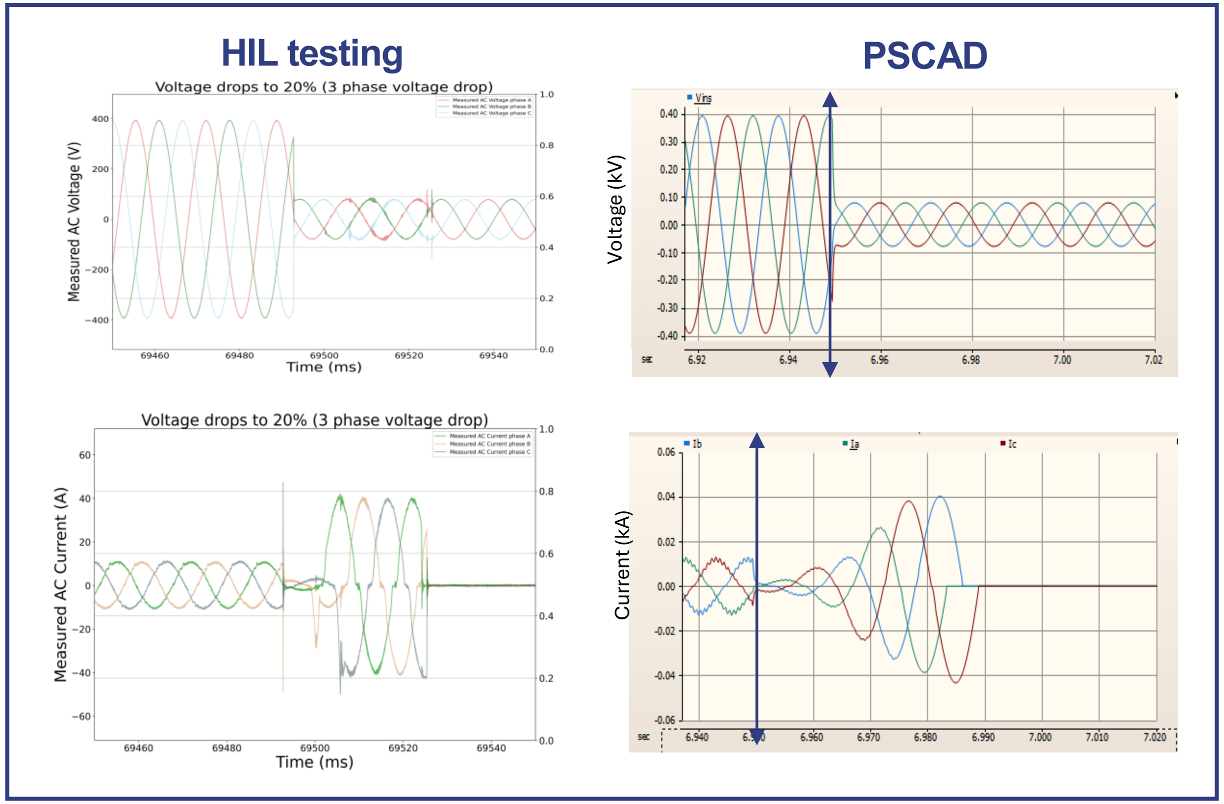


[1] https://www.opencompute.org/wiki/Open_Rack/SpecsAndDesigns

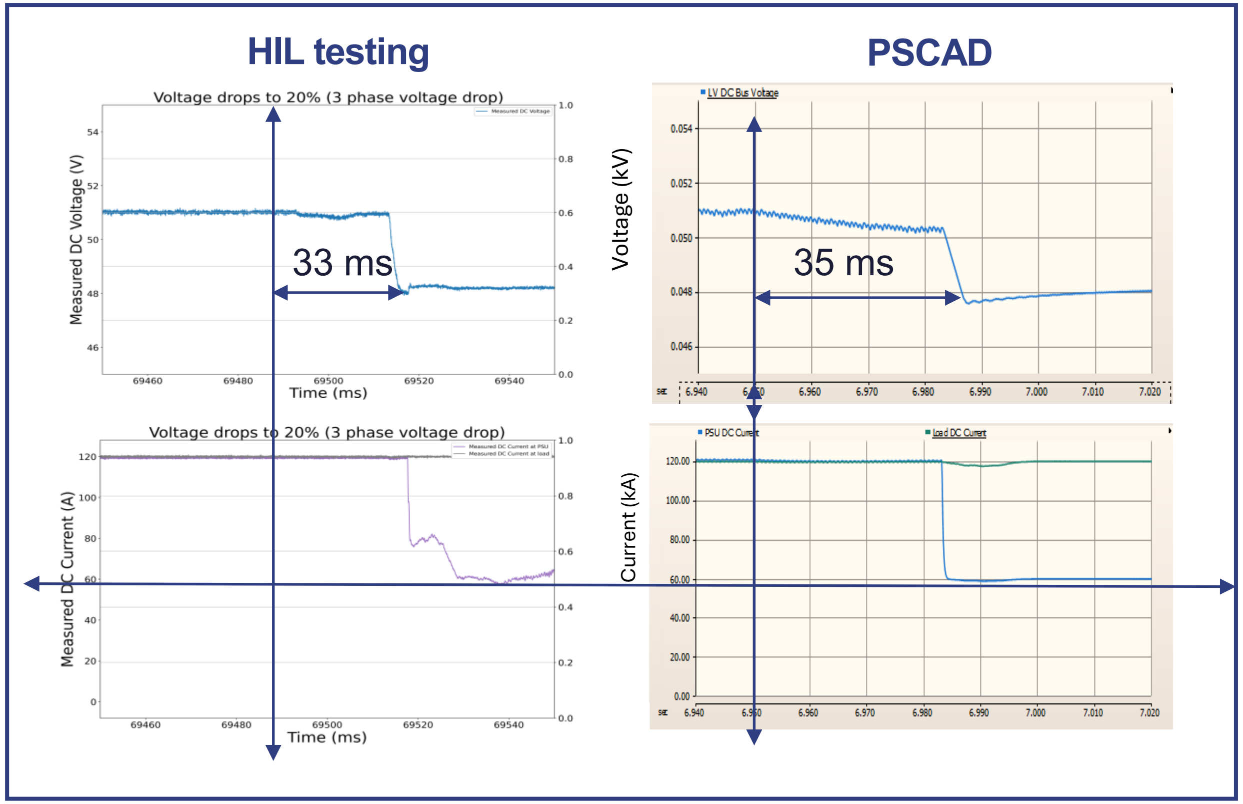


MODEL VALIDATION EXAMPLE

- In this case, system voltage drops to 20% of nominal.
- PSU control and protection settings were adjusted to achieve the same response in both AC and DC sides compared to HIL testing results.



AC-side comparison



DC-side comparison

CONCLUSION

Accurate EMT modeling of data center loads requires detailed characterization of converter behavior, control limits, ride-through settings, and harmonic performance to properly assess system impacts.

Load type and operating profile

- Load type (AI, cloud, crypto, etc.)
- Typical daily load profile (kW vs. time)
- AI load behavior (ramp rates, frequency, duty cycle, etc.)

Cooling loads

- Fan and motor type: direct-coupled induction vs. VFD-controlled
- Motor load as a percentage of total facility load or load block

Electronic load front-end details

- Converter topology: diode bridge & filter, PFC/IGBT, UPS, AFE, etc.
- Control and protection limits that shape current draw
- Operating modes vs voltage (manufacturer/model number)

Distribution system

- Single-line diagram for the load connection
- Step-up transformer details (e.g., three-winding)
- Collector system

Ride-through and protection

- Overvoltage/undervoltage trip thresholds
- Timing and delays for trips and recovery
- Any additional ride-through parameters and settings

Power quality

- Harmonic profile of the load
- Filter type and details (active vs. passive)
- Validation of PSCAD model against OEM spec and test results

QUESTIONS AND DISCUSSION