A QUANTA SERVICES COMPANY

ESIG SUMMER 2026 WORKSHOP

DATA CENTER MODELING FOR LARGE LOAD INTERCONNECTION REQUIREMENTS

Matching study requirements to model fidelity
Requirement category to model type to deliverable

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FRAMING

Two questions:

The problem is not how to build the model — it is knowing which model a requirement demands, and what it must deliver

✓ WELL-ADDRESSED — HOW TO BUILD IT

— PERC1/CMLDBLU2 for phasor studies (PERC2 under development)
— UDM + detailed models for EMT
— Component taxonomy: UPS, IT load, cooling, gensets, BESS
— Model benchmark & validation procedures

⚠ THE GAP — WHICH MODEL, WHAT OUTPUT?

— What study type are we running?
— Which model fidelity is sufficient vs. required?
— What specific outputs must the model produce?
— When does a phasor model fail you?

This talk: requirement category → model type → what the model must deliver

ARCHITECTURE

Data center architecture: where models live

Each layer has distinct electrical behavior — and each maps to a different modeling challenge

GRID / POI	STEP-DOWN XFMR	UPS / RECTIFIER	IT LOAD	COOLING	GEN / BESS
Transmission voltage, SCR	Saturation, tap changer	CPL behavior, power mode	Pulsed, algorithm-driven	Motor loads, VFD/DOL	Transition timing

Requirements are measured at the POI — but the behavior that drives them originates deep in the stack

- **Ride-through:** UPS control mode (constant-power vs. constant-current) drives POI behavior
- **Ramp rate:** IT job scheduler + UPS slew limiter = the grid-facing ramp profile
- **Oscillations:** Load Behavior, Rectifier impedance, PLL dynamics — invisible in phasor models

ROADMAP

Requirement to model type: what each must deliver

Phasor models are sufficient for some requirements and inadequate for others

REQUIREMENT	MODEL TYPE	WHAT THE MODEL MUST DELIVER
Voltage Ride-Through (VRT)	**Phasor (primary) + EMT (detailed)**	Protection setpoints, UPS ride-through settings, multi-event logic
Frequency Ride-Through (FRT)	**Phasor**	Relay frequency settings, UPS transfer timing, RoCoF sensitivity
Post-Fault Active Power Recovery	**Phasor + EMT (validation)**	Recovery ramp slope, UPS-to-grid transfer time, configurable rate
Ramp Rate	**Phasor (aggregate impact)**	P(t) at POI, MW/min P75 statistics, AI job cycle characterization
Oscillation / Converter Stability	**EMT only**	Rectifier impedance, PLL bandwidth, control-loop interactions, AI job cycle characterization/variability
Power Quality	**EMT only**	Harmonics, flicker, RVC

VOLTAGE RIDE-THROUGH

VRT: phasor is sufficient — with the right parameters

Phasor represents the UPS functionally; the true weak-grid failure mode is a stability question, not a VRT one

✓ PHASOR (PERC1) — PRIMARY

— Undervoltage trip threshold + delay — the setpoints that determine compliance
— UPS mode: constant-current (required) vs. constant-power (non-compliant)
— 'Three-strikes' counter reset logic across reclosing events
— Battery SoC window — how long UPS sustains IT load off-grid

⚠ EMT — DETAILED RIDE-THROUGH BEHAVIOR

— Firmware-level constant-current mode validation
— Multi-event reclosing survivability at sub-cycle resolution
— Aggregate load pickup and delayed voltage recovery (see stability)

✗ THE PHASOR LIMITATION — WHERE IT LIVES

— CPL negative-impedance instability is a system-stability question, not VRT compliance
— Phasor models UPS as fixed-P — cannot see the V-I feedback loop

Bottom line: For VRT compliance, the phasor model is adequate — the hard part is acquiring real protection setpoints and confirming constant-current mode. Weak-grid CPL instability belongs in the SCR / stability study.

FREQUENCY RIDE-THROUGH

Protection settings drive everything

Frequency dynamics are well-captured by phasor (RMS) simulation — the work is obtaining the actual relay settings

What the model must reproduce

- Under-/over-frequency relay settings (trip setpoints + delays)
- RoCoF protection: tripping on df/dt vs. absolute frequency
- UPS bypass transfer timing during under-frequency events
- Interaction with facility UFLS — does it shed before grid trip?
- Genset governor response (s) vs. FRT timescale (sub-second)

✓ PHASOR — SUFFICIENT

- Frequency dynamics well-captured by RMS simulation
- Relay Models: frequency-sensitive trip logic representable
- RoCoF trip: PERC1 (NERC/EPRI) with actual relay settings

KEY PARAMETERS TO OBTAIN	
Under-freq trip	59.0–59.5 Hz, 0.1–0.5 s
RoCoF threshold	0.5–2.0 Hz/s (site-specific)
UPS transfer speed	< 4 ms (double-conversion)
UFLS shed level	% of POI load, trigger threshold

POST-FAULT ACTIVE POWER RECOVERY

Recovery shape matters as much as speed

The desired profile is a controlled ramp to 90%(example) within 1–2 s — too fast re-depresses voltage, too slow risks frequency excursion

Recovery scenarios

✗ **Step recovery (too fast)** — re-depresses voltage

✓ **Ramp recovery (controlled)** — 90% in 1–2 s

⚠ **Delayed / stays low** — frequency + thermal risk

What the model must reproduce

— UPS-to-grid handoff timing after V ≥ 0.9 pu crossed
— Configurable recovery ramp rate (firmware-settable)
— Whether recovery triggers constant-current or constant-power
— Aggregate effect — correlated step recovery re-depresses V

For example : Staying connected through 0.50–0.80 pu earns a 2-second recovery window; dropping to zero in that band means 0.5-second recovery. The model must reproduce both branches — and the UPS state that decides which applies.

RAMP RATE

Two study types, two model needs

Aggregate ramp is a phasor stability question; intra-minute fluctuation and flicker are EMT power-quality

✓ PHASOR — AGGREGATE RAMP IMPACT

- P(t) time series at POI — 1-second resolution minimum
- MW/min: P75 of 1-min / rolling window (Tier 1 ≤ 20 MW/min)
- MW/5s: P75 of 5-s intervals (Tier 2 ≤ 10 MW/5s)
- BESS / UPS slew limiter modeled as reduced grid-facing ramp

▸ WHY AI LOAD PROFILES ARE DIFFERENT

- GPU idle ≈ 10%; active ≈ 100–150% — swings of 100s of MW
- Ramp intervals: sub-second to seconds
- Facilities correlated with shared training job scheduler
- Static load model inadequate — need measured P(t)

⚠ EMT — POWER QUALITY & FLICKER

- Sub-second GPU job pulsations result in flicker at POI — EMT to resolve
- Harmonic injection from rectifier front-end during ramps
- UPS stage-switching transients (bypass → normal → generator)

TIER FRAMEWORK

Tier 1	≤ 20 MW/min (10-min rolling, P75)
Tier 2	≤ 10 MW/5s (P75 of 5-s buckets)
Tier 3	Oscillation — study-based limit

OSCILLATION / CONVERTER STABILITY

EMT is not optional

Forced oscillation and converter-driven instability are physically invisible in phasor (RMS) simulation

WHAT THE EMT MODEL MUST REPRESENT

- Rectifier front-end impedance vs. frequency (0.1–1000 Hz)
- Phase-locked loop (PLL) bandwidth and anti-windup logic
- Control-loop interactions (inner current, outer voltage)
- Harmonic filter design (passive vs. active)
- Aggregate multi-infeed interaction factor (wMIIF first)

STUDY TYPES REQUIRING EMT ONLY

- Sub-synchronous resonance (SSTI) with nearby gen
- Sub-synchronous control interaction (SSCI) vs. series caps
- Converter-driven oscillation at low SCR (< 3.0)
- Modal frequency avoidance verification (guard bands)
- Harmonic injection: impedance scan

Screening path: SCR / WSCR / wMIIF → if any threshold is exceeded, a full EMT impedance scan plus time-domain validation is required.

STABILITY ASSESSMENT

Weak-grid interconnections and the EMT trigger

Short-circuit ratio at the POI sets the screening line — below SCR 3, full EMT is required

STRONG SCR > 6	MEDIUM SCR 3–6	WEAK SCR < 3
Phasor sufficient for most requirements	Phasor + EMT screening; VRT validation in EMT	Full EMT for VRT, PFAPR, oscillation

CPL negative-impedance instability

- CPL presents dV/dI < 0: V drops → current rises → V depressed further
- Phasor models load as fixed P — cannot capture the feedback
- EMT models rectifier switching — instability becomes visible
- Trigger: SCR < 3, or aggregate CPL > a significant fraction of bus fault current

Mitigation & model requirements

- Model the UPS firmware constant-current mode switch
- Co-located BESS absorbs CPL ramp — model charge/discharge control
- STATCOM reactive injection during sag — model the droop control
- SPP HILL screening: SCR/WSCR/CSCR ≥ 6.0 (no EMT) + CCT ≥ 0.15 s

THE OPEN GAP

Model validation is the unsolved problem

We can build the models — the ecosystem to prove they are right does not yet exist

⚠ No equipment-level test protocol

Ride-through curves are specified at the POI, but no IEC/UL standard lets a developer verify their UPS fleet will comply before interconnection. Manufacturers design to evolving, inconsistent curves.

⚙ Firmware version sensitivity

Recovery ramp, protection thresholds, and CPL/CC switch logic are firmware-settable and can change after the study. Field configuration must be locked and audited.

■ PERC1 is a starting point

The load model represents key DC behaviors but does not natively capture PLL dynamics, CPL instability, or UPS mode-switching for rigorous VRT and oscillation studies.

◆ Aggregate behavior is unstudied

Multiple DCs on one bus may ramp simultaneously (correlated AI schedulers). Existing studies treat facilities independently. Aggregate phasor + statistical ramp correlation is an open research area.

Conclusions: what drives model fidelity

The models exist — the validation ecosystem does not

01 **Requirement category drives model fidelity**
Phasor handles VRT, FRT, transient stability, and aggregate ramp impact. EMT owns power quality, system strength, oscillations, and CPL instability.

02 **For VRT, phasor is sufficient — but only with the right parameters**
Protection setpoints, UPS ride-through mode (constant current, not CPL), and UDM submission. The model is adequate; the data acquisition is the hard part.

03 **Phasor models are blind to CPL instability and converter oscillations**
These require explicit EMT representation. SCR / WSCR screening defines the EMT trigger threshold.

04 **Model validation is the unsolved problem**
Equipment test standards, firmware audits, and aggregate correlated behavior are the open gaps.

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