

# GRID EMT

## SIMULATION INITIATIVE

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### Advanced Data Center Model

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# Verification Challenges in Advanced Large Load EMT Models

Large load EMT models are converter-dominated, with control-driven behavior, and multi-timescale dynamics. Consequently, the model often fails to reproduce real system behavior, hence poor representation of:

- Control logic
- Protection response
- Ride-through performance

Additionally:

- No standard models are available or no guidelines on model usage (and no models in some cases)
- Simulations of 100s of power electronic detailed switched models for seconds can take days
- Without verification, EMT models cannot be trusted for grid-level reliability studies.



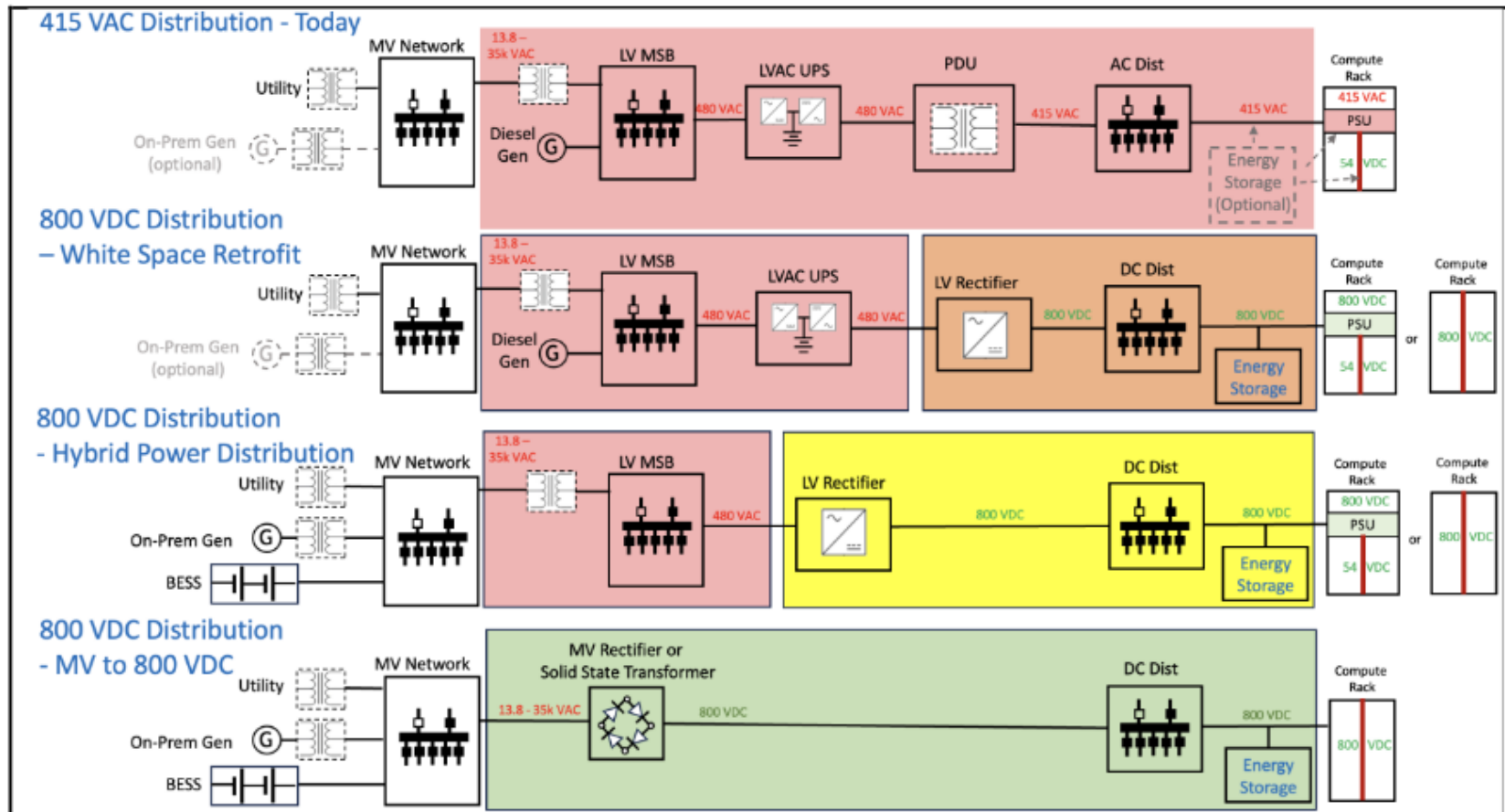
# An Emerging Scenario: Data Centers with AI Loads

AI data centers require modeling and verification for:

- Power electronic conversion stages, e.g., Solid-state transformers (SSTs)
- UPS (except for crypto-mining models)
- DC bus structures
- Load side compute behaviors
- Energy storage systems (ESS), etc.



# Power Delivery Architecture for AI Datacenters



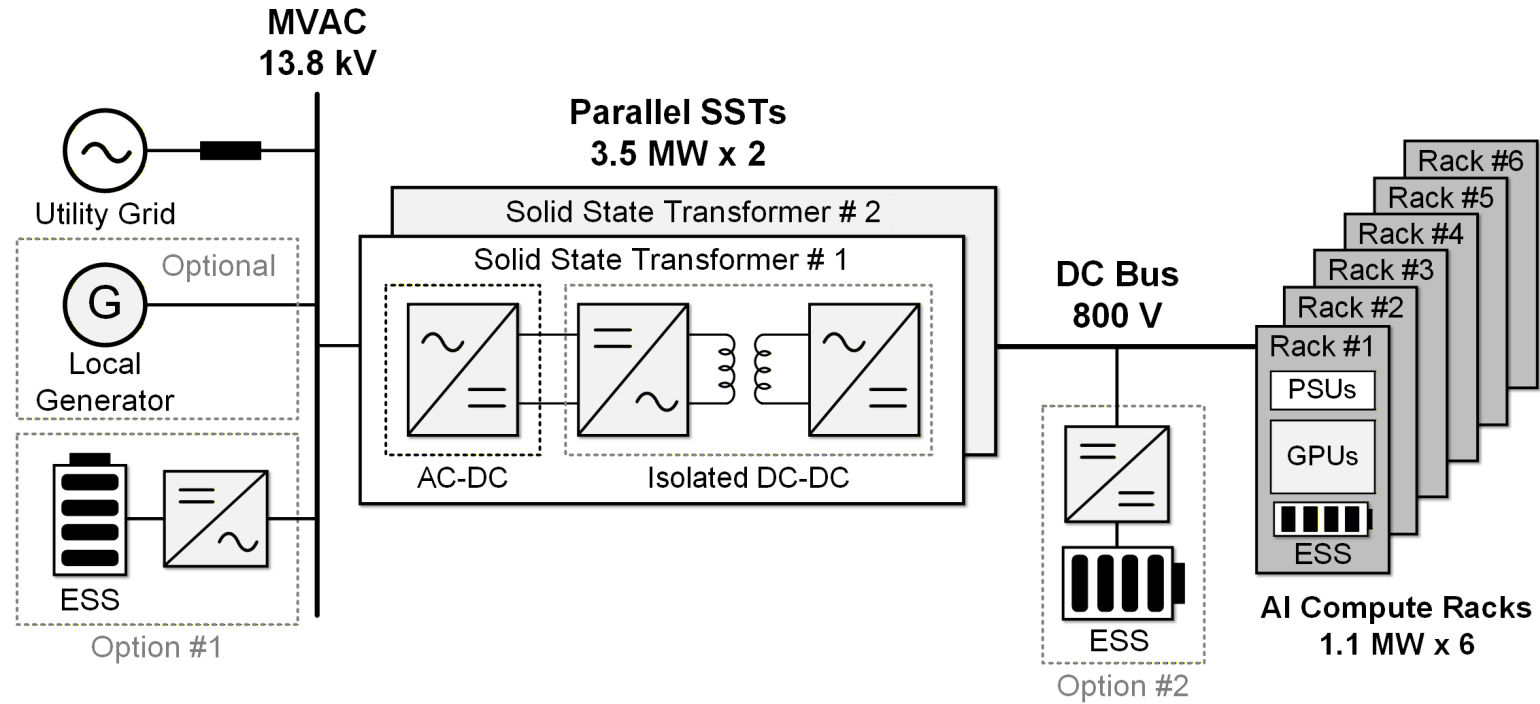
Source: NVIDIA



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# Emerging Grid-to-IT Power Architecture



[Architecture of an 800-V DC power distribution system for AI data centers]

\* Power level is a scaled down version of [NVIDIA's 17.5 MW datacenter reference design](#)

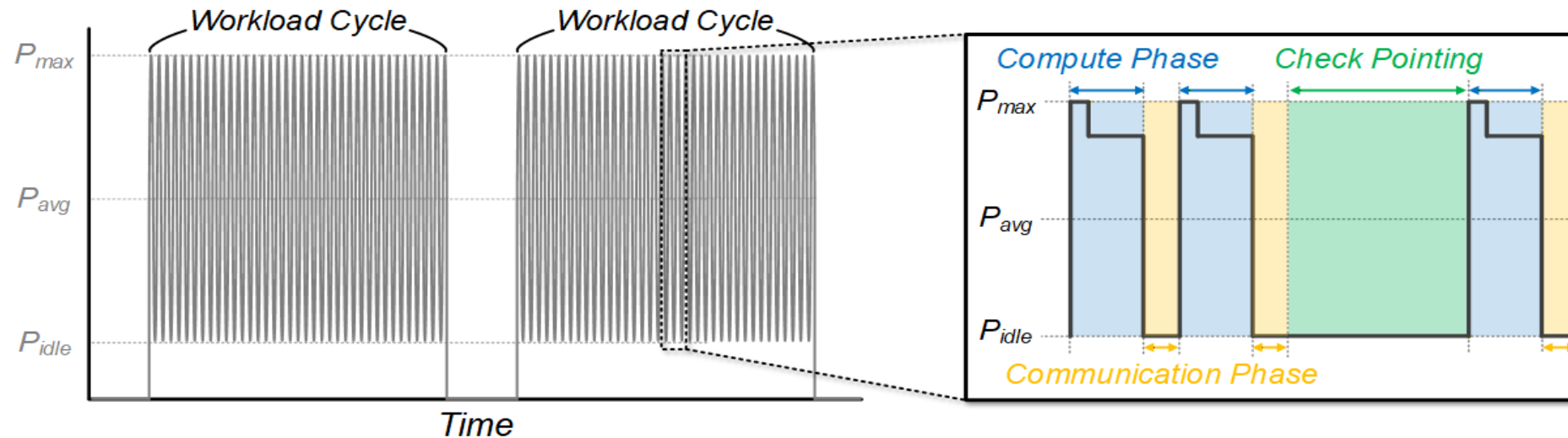


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# AI Data Center Load Characteristics

## Power Fluctuations in AI Data Center Load Demand



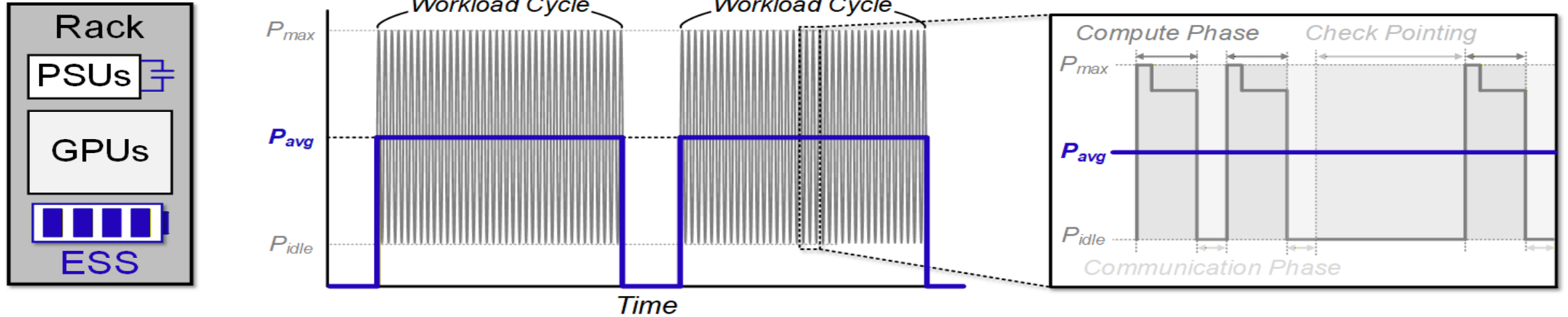
- AI data center loads exhibit power fluctuations across multiple time scales, which can be categorized as follows:
  - 1) Repeated **Compute & Communication phases**: Periodic behavior with time scales **below 100 ms**
  - 2) **Checkpointing** (model/state saving): Periodic events on the order of **1–5 s**
  - 3) **Workload execution cycles**: Periodic variations over **several minutes**

These power ripples should be mitigated by placing energy storage systems (ESSs) at appropriate locations.



# AI Data Center Load Characteristics

## AI Data Center Load Demand with ESSs

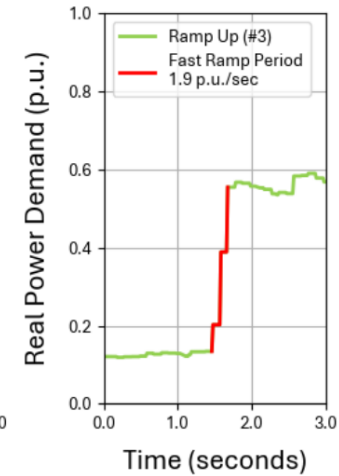
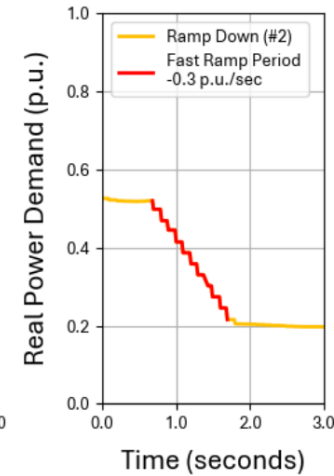
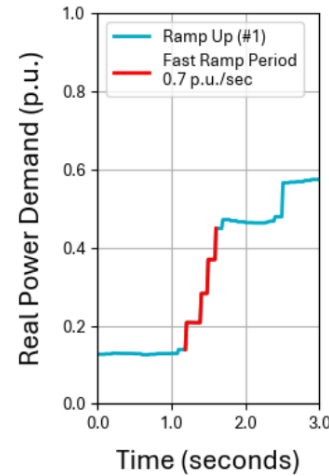
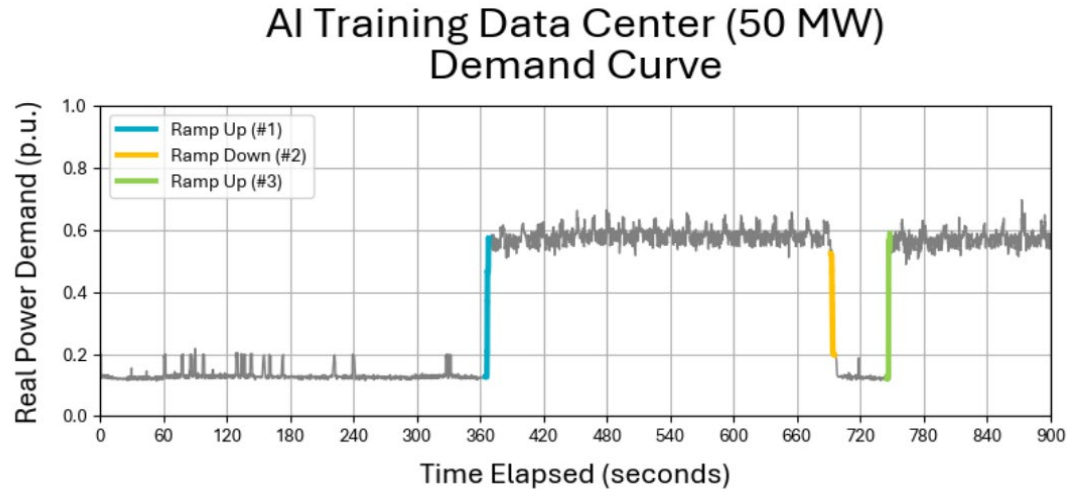


- AI data center loads exhibit power fluctuations across multiple time scales, which can be categorized as follows:
  - 1) Compute & Communication phases (sub-100 ms): **Output Capacitor of PSUs** and **Additional Electrolytic Capacitors**
  - 2) Checkpointing (model/state saving) (1–5 s): **Rack-level ESSs (Super Capacitors)**→ Rack-level ESSs can effectively mitigate high-frequency power ripples. However, the **utility grid still experiences step load variations** at the minute-level time scale.



# AI Data Center Load Characteristics

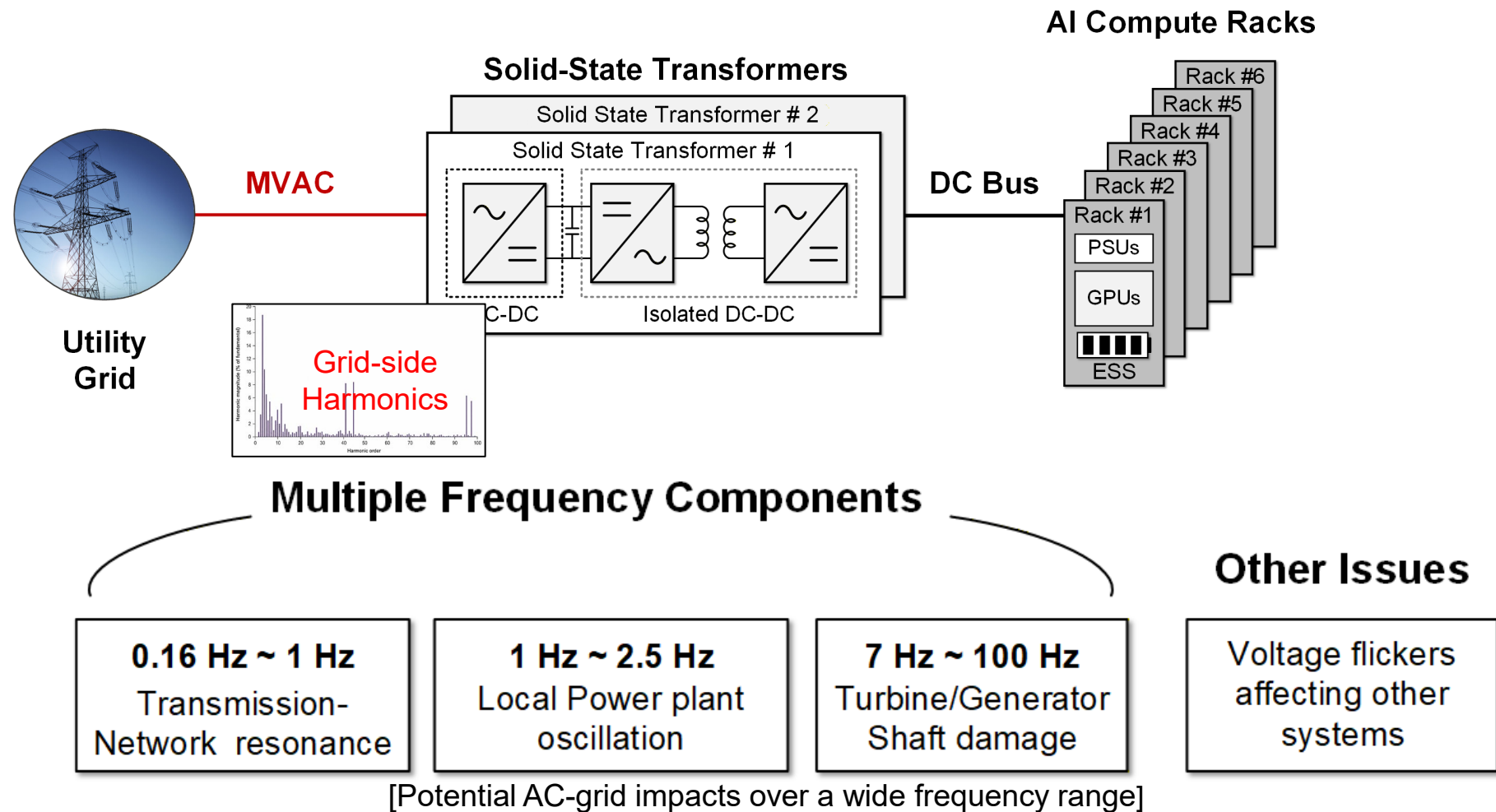
## AI Data Center Load Demand : Ramp Up/Down



- Even with rack-level ESSs, AI data center loads can still exhibit rapid ramp-up/down behavior.
- These rapid load variations pose a significant challenge from the grid perspective.



# AC Grid Interconnection Concerns



# Need for EMT Simulation

Future data centers are characterized by:

- Thousands of grid-connected converters
- Solid-state transformers (SSTs)
- AC/DC and DC/DC converters
- Battery energy storage systems
- UPS systems
- High-power GPU power supplies
- DC distribution networks (e.g., 800V, HVDC architectures)

As a result, the electrical infrastructure becomes **converter-dominated rather than machine dominated**.



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# Standardized EMT Model Verification Requirement

Model Verification should follow NERC's guidelines.

- **Core requirements:**
  - Parameter transparency
  - Full traceability
- **Model quality dimensions:**
  - Accuracy, fidelity, usability, and efficiency



# Verification Test Structure for EMT Models

## Model Adequacy Tests

- Usability, numerical stability, and computational efficiency

## Functional Tests

- Power command tracking, output limits and ramp rates, grid support functions

## Ride-through Tests

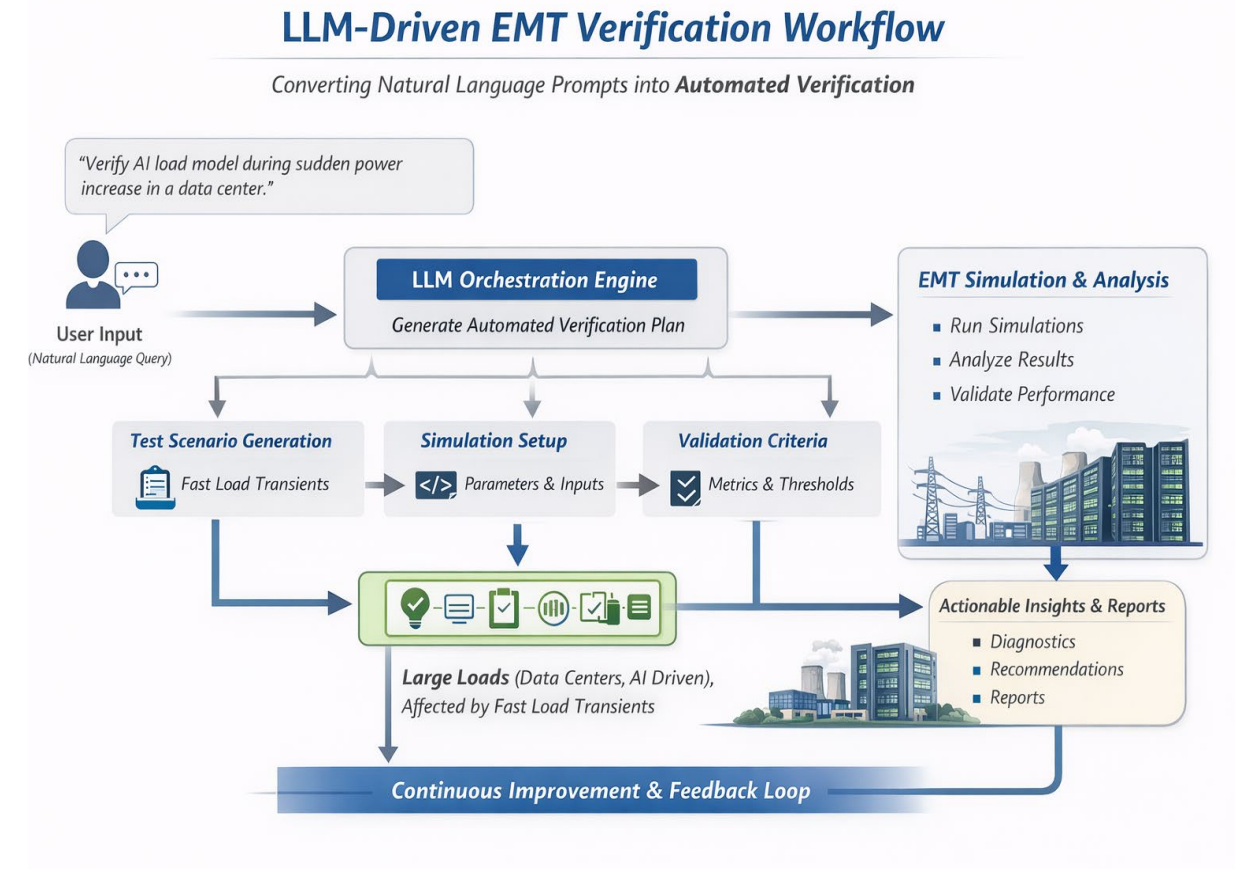
- Voltage and frequency, faults, fast load transients, recovery behavior after disturbance and benchmark setup



# Approach: LLM-Assisted Automation for Model Verification

## LLM-enabled capabilities:

- Automated interpretation of simulation results
- Scalable verification across benchmark scenarios
- Explainable diagnostics for model behavior



# Why Disaggregation is Important for EMT-Level Modeling?

## Limitations of Aggregated Load Models

- Aggregated models can mask the internal behavior of modern loads.
- Different subsystems may have distinct:
  - Controls
  - Protection functions
  - Dynamic responses

## Why Disaggregation Matters

- Reveals the composition of large loads (e.g., servers, UPS systems, HVAC drives, batteries in a data center).
- Enables accurate modeling of:
  - Fault response and ride-through, converter-grid interactions, harmonic and resonance phenomena, and stability and oscillatory behavior

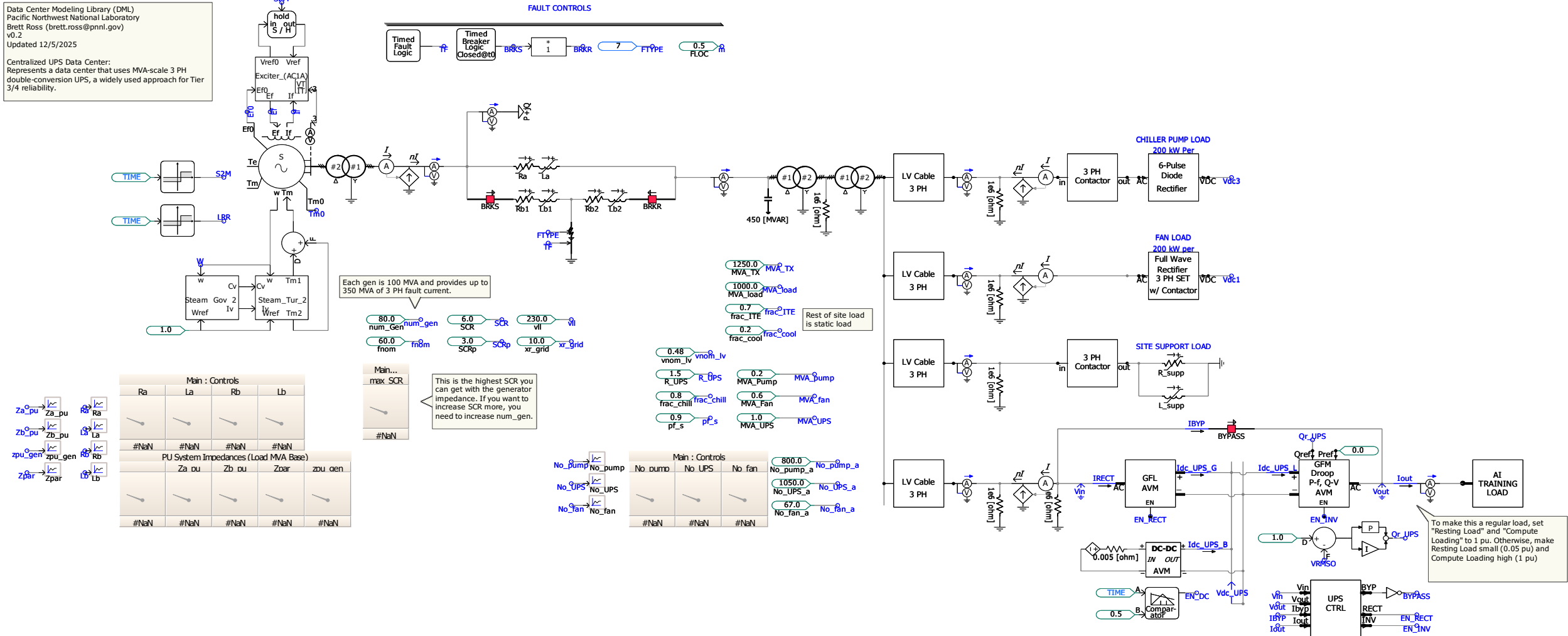


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# Initial Aggregated Data Center Model

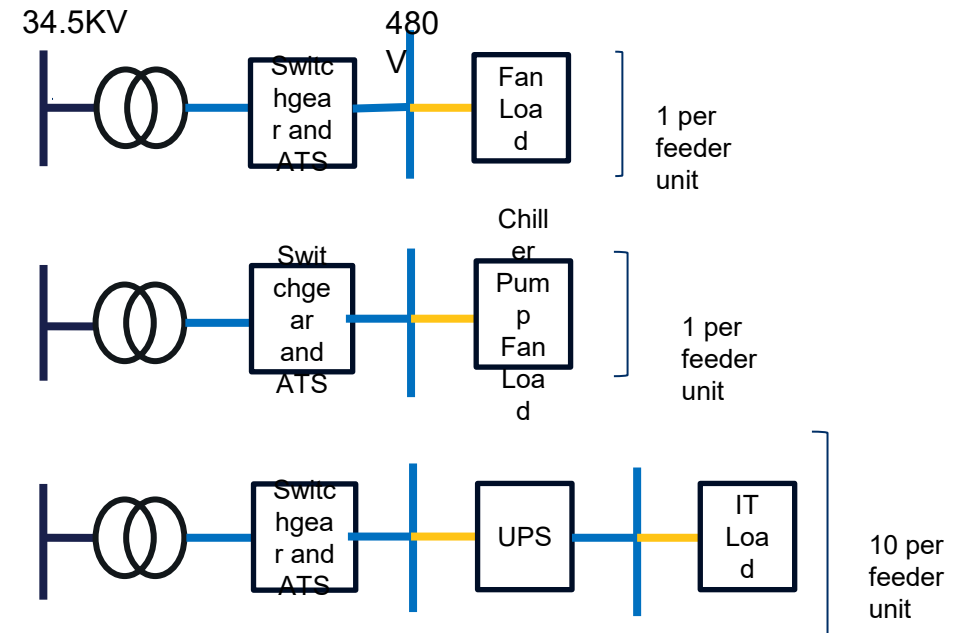
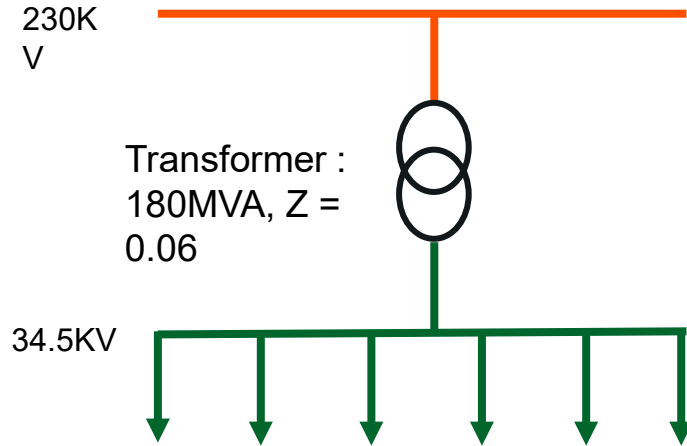
The original model represented the data center as a single equivalent load supplied through an aggregated UPS system



# Development of the Disaggregated Model

The aggregated model was progressively expanded by introducing individual feeder units and detailed UPS representations

## HV System

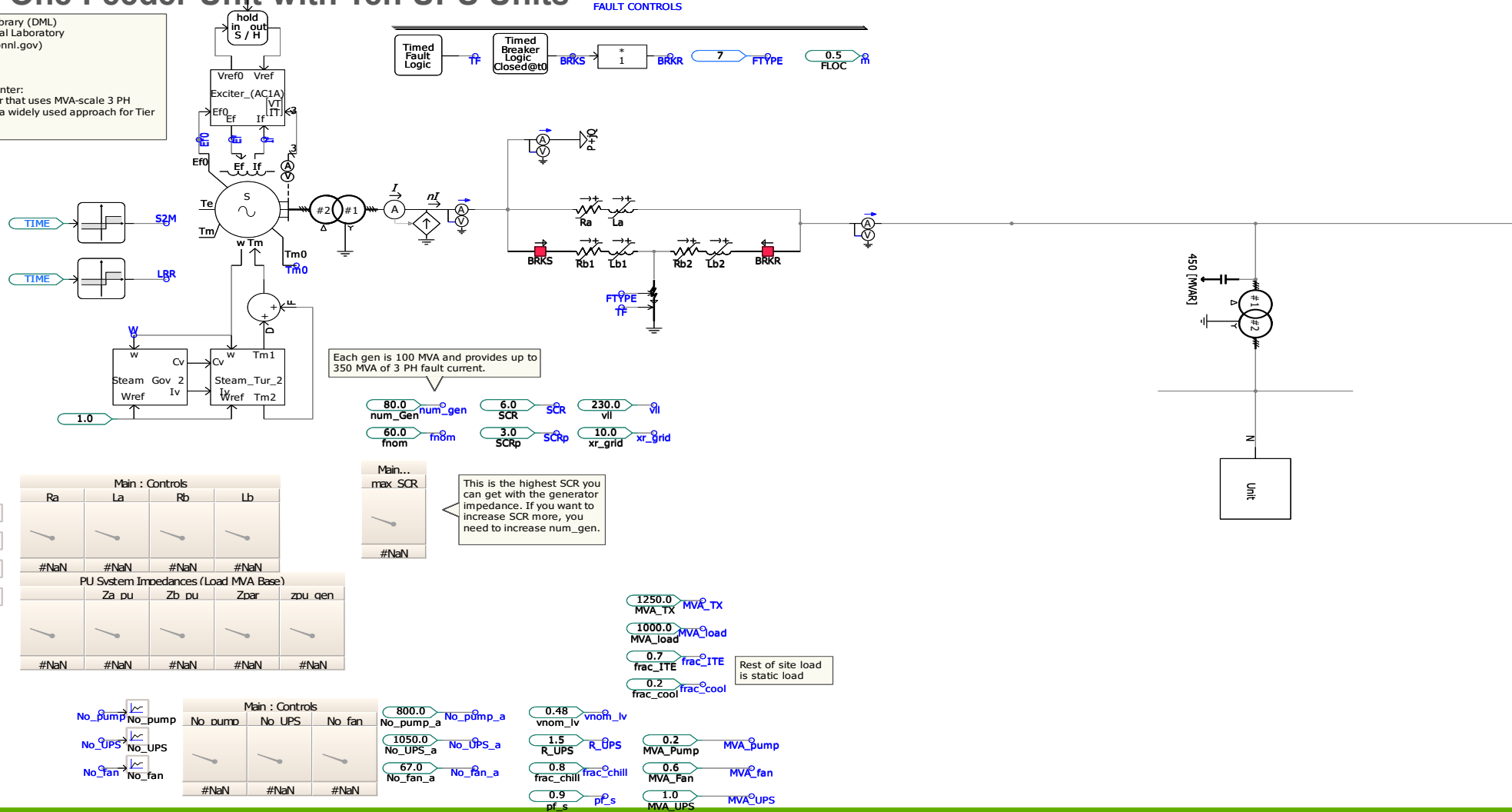


# Current Disaggregated Model Configurations

## Model 1: One Feeder Unit with Ten UPS Units

Data Center Modeling Library (DML)  
Pacific Northwest National Laboratory  
Brett Ross (brett.ross@pnnl.gov)  
v0.2  
Updated 12/5/2025

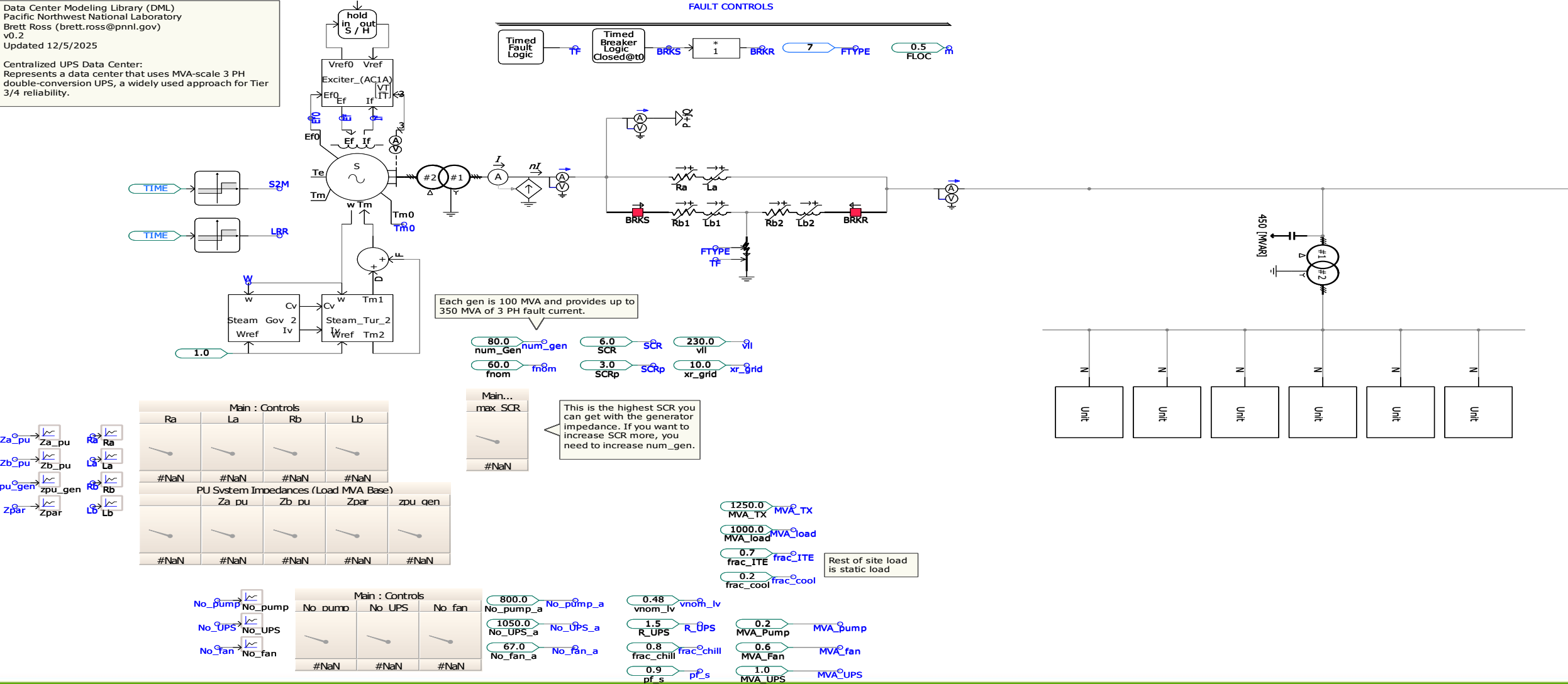
Centralized UPS Data Center:  
Represents a data center that uses MVA-scale 3 PH  
double-conversion UPS, a widely used approach for Tier  
3/4 reliability.



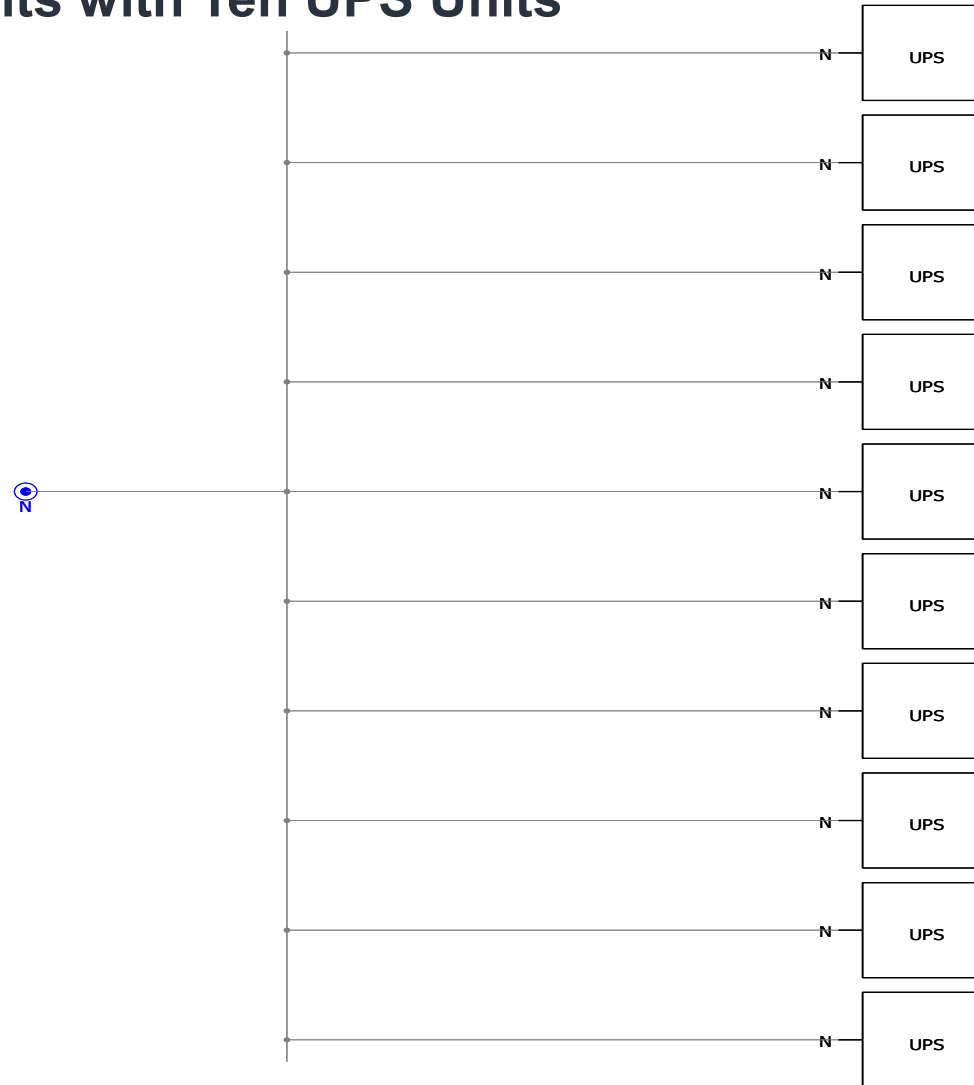
• Model 2: Six Feeder Units with One UPS Unit

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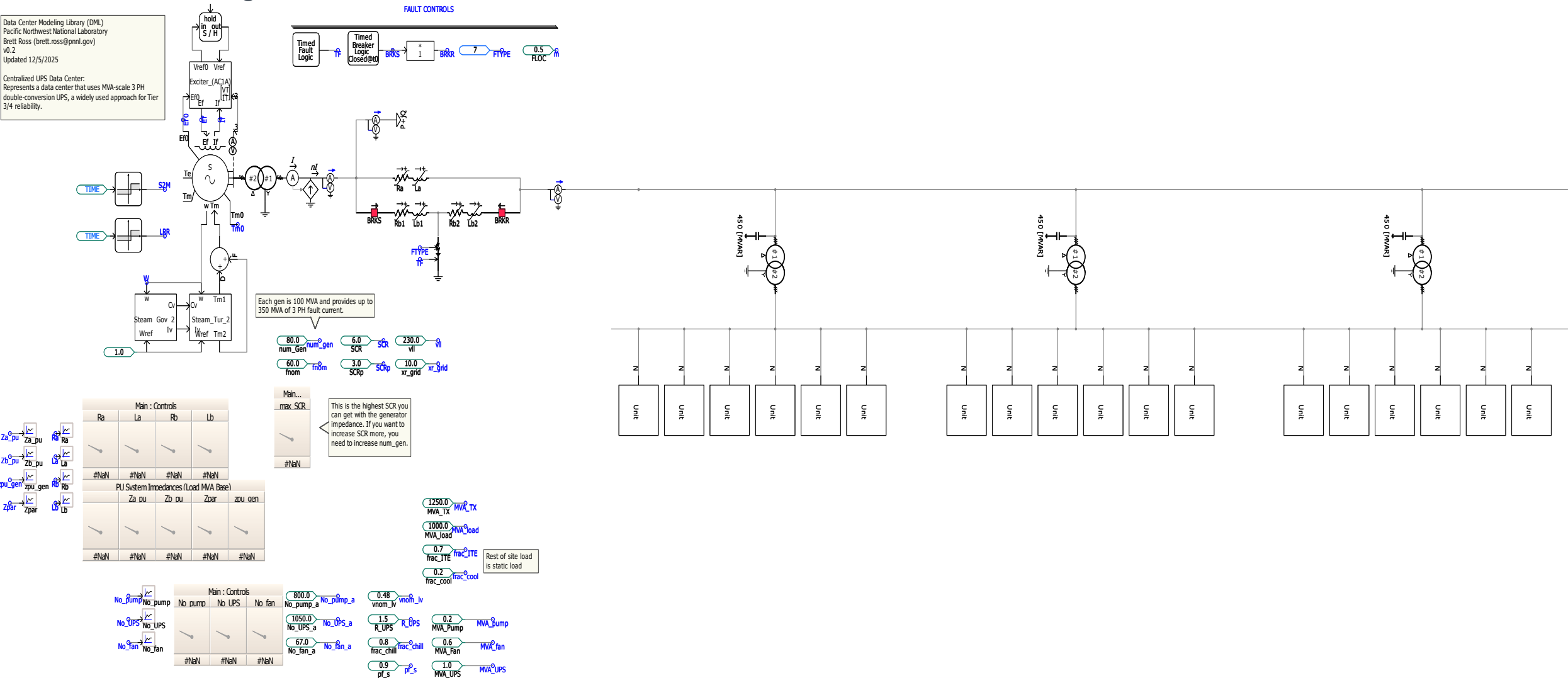
- Model 3: Six Feeder Units with Ten UPS Units



- **Model 4: Eighteen Feeder Units with One UPS Unit**

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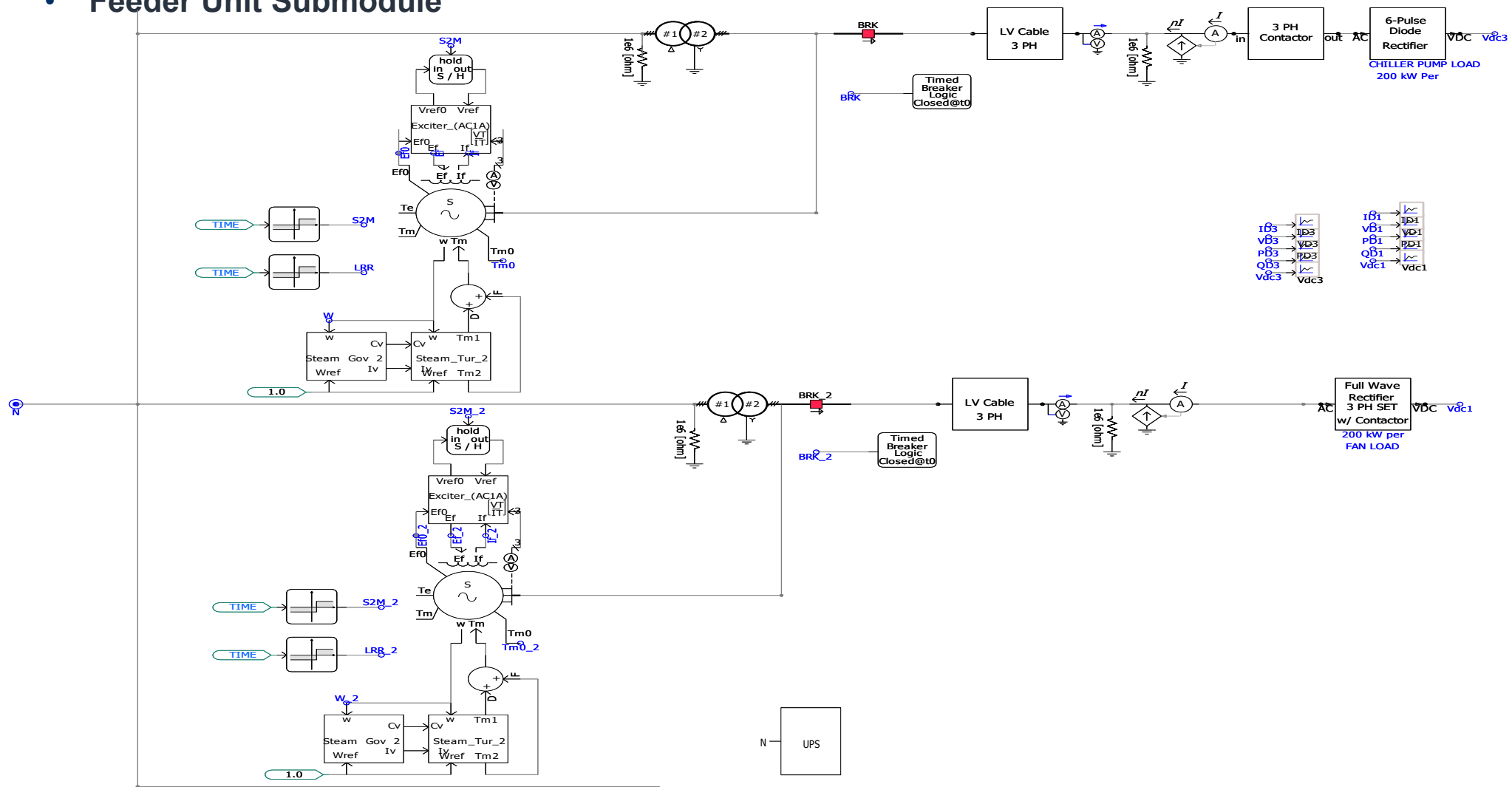
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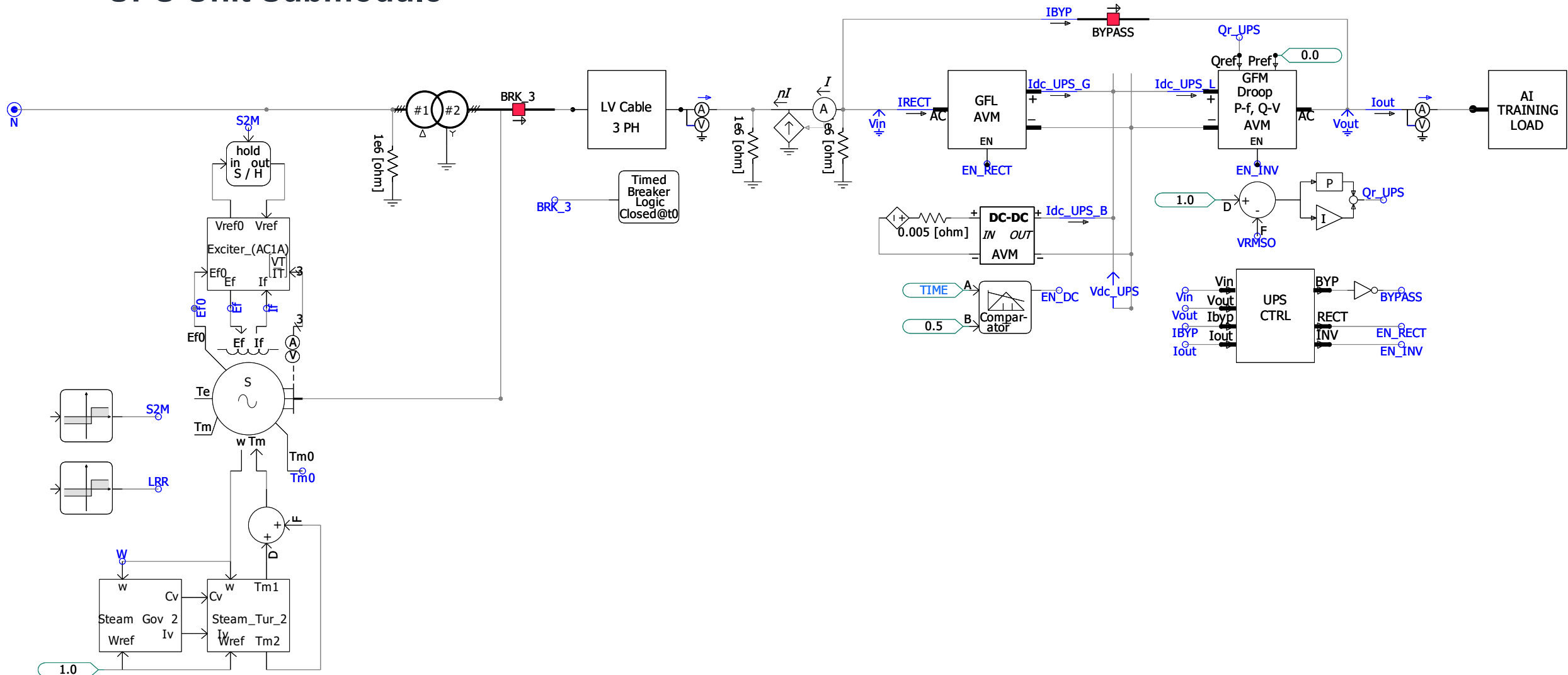
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# Feeder Unit Submodule



# • UPS Unit Submodule



# Next Steps: Workflow

Large Load Architecture (Aggregated Models)



Disaggregated EMT Models



Verification & Ride-through Testing



Simulation Outputs / Logs



LLM-based Interpretation



RE-INTEGRATE Integration



Automated Diagnostics & User Support



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# Impact: LLM-Driven EMT Verification & User Experience

- **Transforms verification workflow:** Converts natural language prompts into automated EMT validation (test cases, inputs, metrics)
- **Accelerates analysis:** Reduces setup time, enabling faster iteration and decision-making
- **Improves consistency:** Standardizes verification procedures across users and studies
- **Scales to complex systems:** Enables efficient validation of large-load models (e.g., data centers)
- **Enhances usability:** Provides explainable insights, reducing reliance on expert interpretation

**Outcome:** Faster, more reliable, and scalable EMT model validation with LLM-guided workflows



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# Impacts Expected

- Integrating EMT models of large AI-driven loads such as data centers with the RE-INTEGRATE platform/tool enables a much more physics-accurate, system-level, and time-synchronized representation of modern power systems under high-performance computing demand.
- **It enables following key capabilities:**
  - High-fidelity grid-load interaction modeling (EMT scale)
  - Move forward with standardization
  - Scenario-based planning and digital twin capability
  - Ride-through and resilience assessment



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# References

- [1] B. A. Ross and J. Follum, *Electromagnetic Transient Modeling of Large Data Centers for Grid-Level Studies*, PNNL-38817, Pacific Northwest National Laboratory, Richland, WA, USA, Dec. 2025.
- [2] Pacific Northwest National Laboratory, *DML\_DC2\_Central\_UPS*, PSCAD model, 2025.
- [3] NERC, Reliability Guideline Electromagnetic Transient Modeling for BPS Connected Inverter-Based Resources—Recommended Model Requirements and Verification Practices, [https://www.nerc.com/globalassets/who-we-are/standing-committees/rstc/irps/reliability\\_guideline-emt\\_modeling\\_and\\_simulations.pdf](https://www.nerc.com/globalassets/who-we-are/standing-committees/rstc/irps/reliability_guideline-emt_modeling_and_simulations.pdf)



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# Thank You

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