**ELECTRICAL AND COMPUTER ENGINEERING**

# Large Load Modeling
# for Grid Impact Analysis

Ning Lu

Electrical and Computer Engineering Department

**NC STATE**

# NERC "Large Load" Definition

*"Any **commercial or industrial individual 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**"*

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# What are the large loads?

| Category | Typical Large Loads | Main Characteristics |
|---|---|---|
| Industrial Large Loads | Metallurgy, chemical plants, mining, semiconductors manufacturing, etc. | High power, continuous or heavy-duty operation |
| Infrastructure Loads | Metro, high-speed rail, water & sewage plants | Regional concentration, time-sensitive |
| Hospitals & Communication Hubs | Large hospitals, telecom centers | Critical life-safety loads |
| Interruptible Large Loads | Arc furnaces, flexible manufacturing | Power-intensive but stoppable |
| Commercial Large Loads | Malls, office complexes, stadiums | Peak-demand driven (HVAC dominant) |
| **New-Types of Large Loads** | Cryptocurrency Mining **Data centers (IDC)** | **High power density, strict reliability** |
| | **Hydrogen Production, EV charging hubs** | **High power density, Operational flexible** |

**In ERCORT Loads > 75MW. More than 100 GW in the queue.**

**Professor Ning Lu, North Carolina State University, 2/4/2026, Page 3**

# What are the impacts of large loads?

- They are generally ≥ 75 MW (Data Centers can be > 1GW)

- Require a **Large Load Interconnection Study (LLIS)**
  - May require **new transmission upgrades or multiple substations**
  - May need **onsite generation > 100MW for meeting reliability, adequacy, and stability requirements**
  - May need **UPS, super capacitors, battery storage for backup power**

- Impacts
  - Large load variations can induce generator **oscillations** and uncontrolled tripping
  - cause local **voltage depressions (power quality issues)**
  - may trip during normally cleared faults.
  - cause large **voltage disturbances** and **frequency** overshoot, resulting cascading failure
  - Increasing the need for fast frequency response (FFR).

- Avoid load dropping/increasing  "too much, too fast"
  - **Voltage ride-through** capability is required (e.g., 9-cycle fault clearing).
  - A minimum remaining-on capacity may be required post-fault to prevent cascading disturbances.
  - For example: 1GW data center should have say a minimum of 500 MW remaining after the fault is cleared or limiting the load changes to be within 200MW.

- **Require new dynamic load models.**

# Planning and Operational Issues

Where to put generation/CAP/UPS/battery resources? Capacity of them? Coordinations?
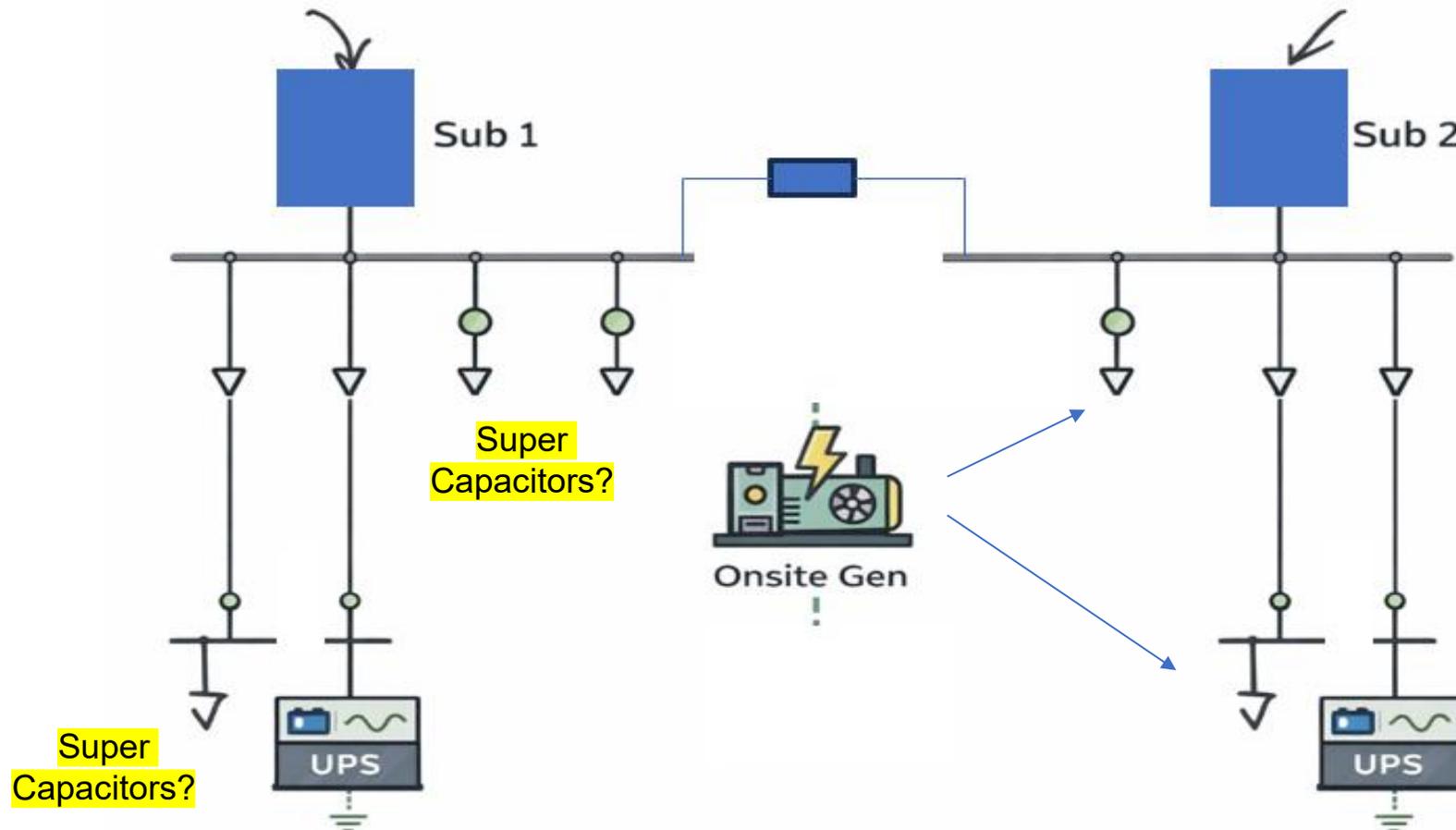
# What load characteristics may be desired?
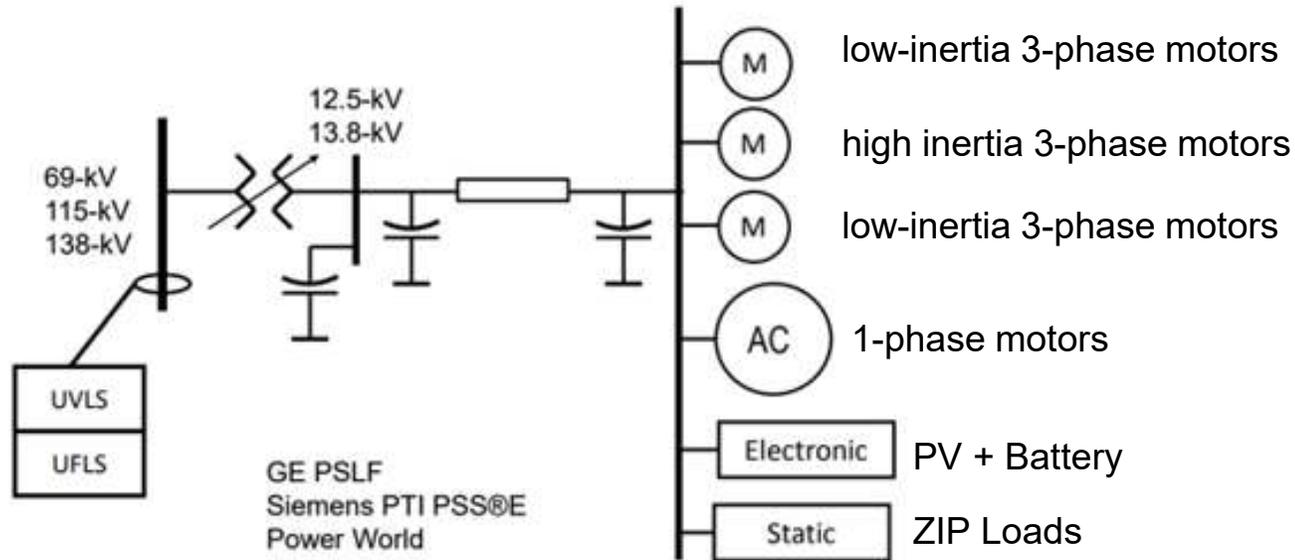
- The dynamic response of **Large Load Interconnection Study** may evaluate:
  - Frequency nadir / overshoot
  - Rate Of Change Of Frequency (ROCOF)
  - Voltage recovery
  - Generator responses
- We may need to specify
  - Maximum instantaneous load loss (MW)
  - Minimum post-fault retained load
  - Required staged shedding (e.g., blocks of 50–100 MW)
  - Load ramp-down / ramp-up rates
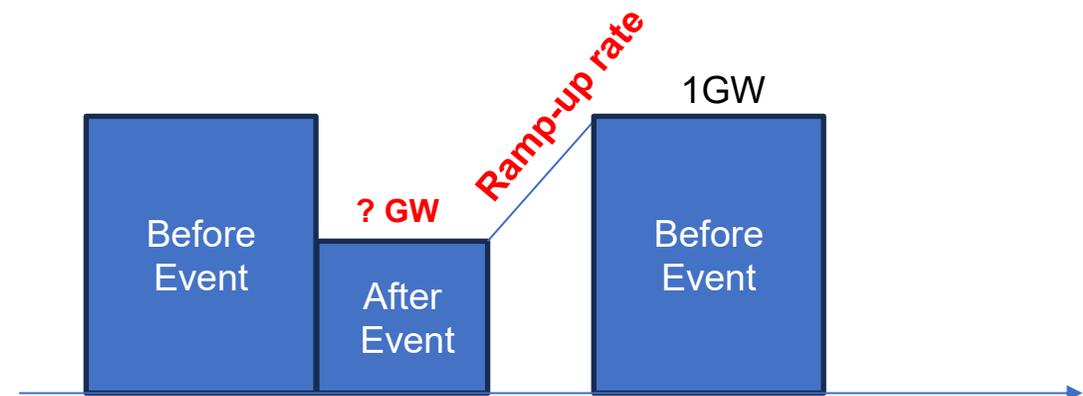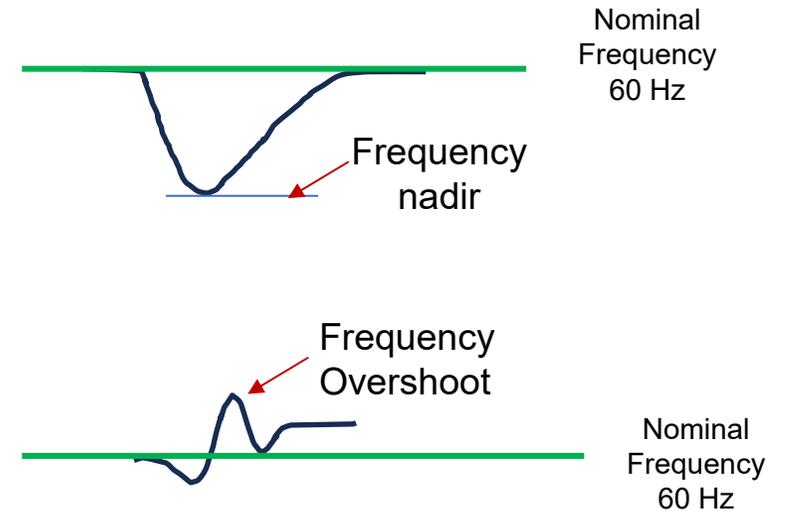
# Dynamic Load Models for a Data Center

| Category | Typical Large Loads | Main Characteristics | Typical Load Models |
|---|---|---|---|
| **Data Centers (IDC)** | **AI Training, Cloud computing,** | **High power density, near-constant load, high power quality** | **ZIP (P-dominant), Motors, Large synchronous Generators, UPS, Super Capacitors, IBRs: Batteries, PV farms, etc.** |
| EV Charging Loads | Fast charging stations, fleet depots | Highly stochastic, clustered demand, power electronics dominated | Constant Power (P)+Power Electronics |
| Commercial Building Loads | Office complexes, malls, stadiums | Strong daily/seasonal variation, HVAC-dominated | ZIP models (Z + I dominant), aggregated motor models |

# Can we use the composite load model?



12.5-kV
13.8-kV

69-kV
115-kV
138-kV

UVLS

UFLS

GE PSLF
Siemens PTI PSS®E
Power World

- M — low-inertia 3-phase motors
- M — high inertia 3-phase motors
- M — low-inertia 3-phase motors
- AC — 1-phase motors
- Electronic — PV + Battery
- Static — ZIP Loads

- The composite load model is an aggregated load representation.

- Primarily intended to capture the behavior of various motor-driven loads.

- It is not specifically designed for modeling data centers.

| Motor | etrq Value | Typical Loads | Inertia |
|---|---|---|---|
| A | 0 | Constant torque (e.g. A/C compressors, refrigeration, positive displacement pumps) | Low inertia motor (e.g. H=0.1) |
| B | 2 | Speed² torque (e.g. Large commercial ventilation fans, air handling systems) | High inertia motor (e.g. H=0.5) |
| C | 2 | Speed² torque (e.g. Centrifugal pumps) | Low inertia motor (e.g. H=0.1) |

# Integrated T&D Models

# A Digital Twin based Approach

# Our Existing Microgrid Digital Twin Layout



**Remote Systems**

**Microgrid Control System**

Measurements    Commands

**Remote Communication Interface (File-sharing or VPN)**

**Local Communication Interface (API, Database,…)**

**eMEGASIM**
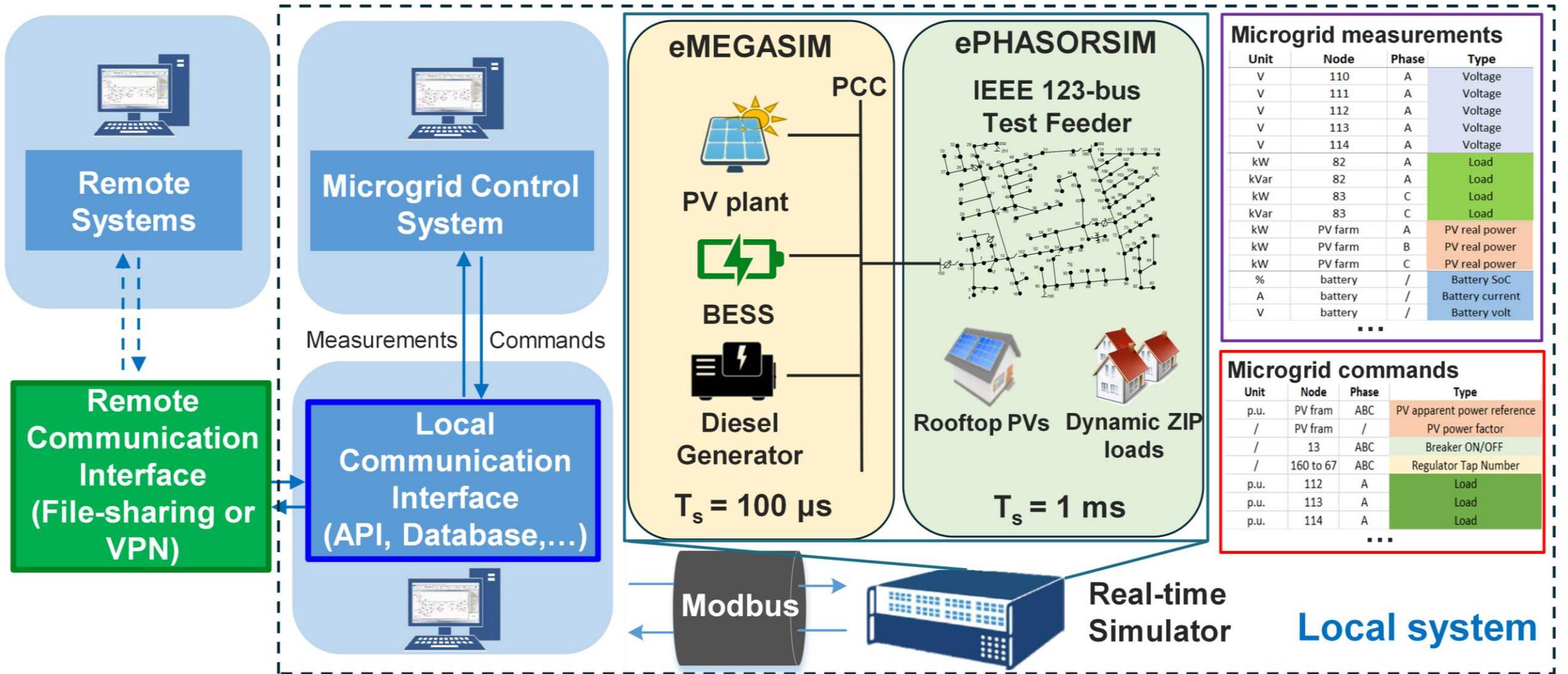
PCC

PV plant

BESS

Diesel Generator

$T_s$ = 100 µs

**ePHASORSIM**

IEEE 123-bus Test Feeder

Rooftop PVs    Dynamic ZIP loads

$T_s$ = 1 ms

Modbus

**Real-time Simulator**

**Local system**

### Microgrid measurements

| Unit | Node | Phase | Type |
|------|------|-------|------|
| V | 110 | A | Voltage |
| V | 111 | A | Voltage |
| V | 112 | A | Voltage |
| V | 113 | A | Voltage |
| V | 114 | A | Voltage |
| kW | 82 | A | Load |
| kVar | 82 | A | Load |
| kW | 83 | C | Load |
| kVar | 83 | C | Load |
| kW | PV farm | A | PV real power |
| kW | PV farm | B | PV real power |
| kW | PV farm | C | PV real power |
| % | battery | / | Battery SoC |
| A | battery | / | Battery current |
| V | battery | / | Battery volt |
| ... | | | |

### Microgrid commands

| Unit | Node | Phase | Type |
|------|------|-------|------|
| p.u. | PV fram | ABC | PV apparent power reference |
| / | PV fram | / | PV power factor |
| / | 13 | ABC | Breaker ON/OFF |
| / | 160 to 67 | ABC | Regulator Tap Number |
| p.u. | 112 | A | Load |
| p.u. | 113 | A | Load |
| p.u. | 114 | A | Load |
| ... | | | |

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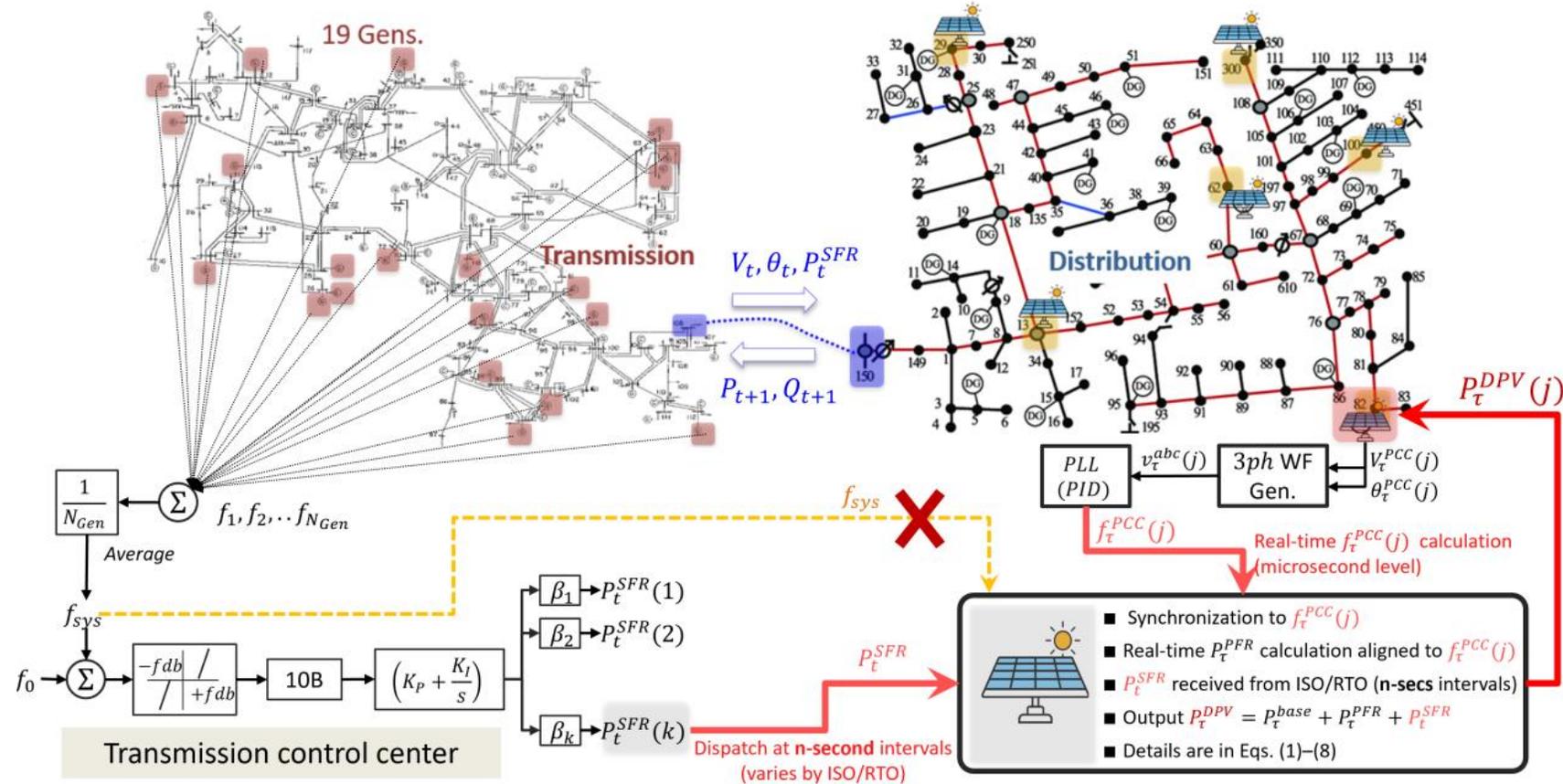
# Data Center Digital Twin Layout



**5) Short-term Load Forecasting**
**6) Energy Management**
**7) Adaptive IT Workload Scheduling**

Remote Systems

Microgrid Control System

Measurements    Commands

Remote Communication Interface (File-sharing or VPN)

Local Communication Interface (API, Database,...)

**eMEGASIM**

PCC

PV plant

BESS

**4) Onsite Generations**
Gas Turbines, Combined Cycle Generators and Batteries

**ePHASORSIM**

IEEE 123-bus Test Feeder

**3) Denser** Distribution Networks

**1) Multiple feeders**
**2) New load models**
 - IT tasks
 - Cooling needs
 - Lighting loads

$T_s = 1$ ms

### Microgrid measurements

| Unit | Node | Phase | Type |
|------|------|-------|------|
| V | 110 | A | Voltage |
| V | 111 | A | Voltage |
| V | 112 | A | Voltage |
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| kW | 82 | A | Load |
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| kW | PV farm | A | PV real power |
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| % | battery | / | Battery SoC |
| A | battery | / | Battery current |
| V | battery | / | Battery volt |
| ... | | | |

### Microgrid commands

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| ... | | | |

Modbus

Real-time Simulator

**Local system**

# Integrated Simulation



Title: Accurate Frequency Response Modeling in Integrated T&D Co-Simulation via RETA-Based Quadratic Extrapolation
JH Woo, Q Xiao, Y Ma, Z Yang, VD Paduani, N Lu. Available at SSRN 5508821•papers.ssrn.com

# Load Data Processing

- Enable **automated processing and analysis of data center load data**

- Identify distinct load characteristics and operating patterns

- Accurately model data center load dynamics and transient behavior

- Inform sizing and operational requirements for on-site generation

- Determine on-site energy storage needs, including batteries, supercapacitors, and UPS systems

- Support advanced energy management, control, and optimization strategies

IT computing Load Type 1

IT Computing Load Type 2

Cooling Loads
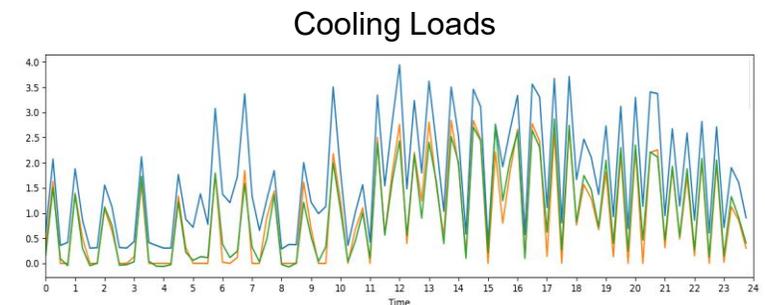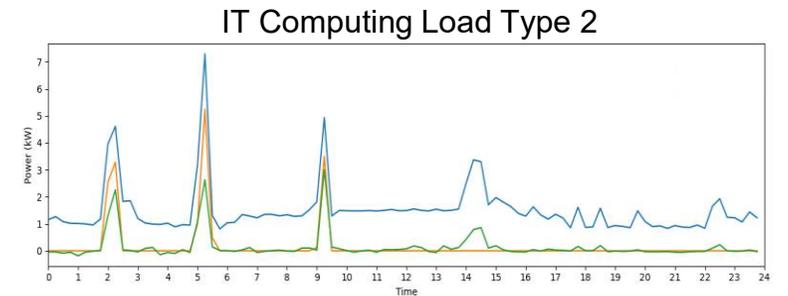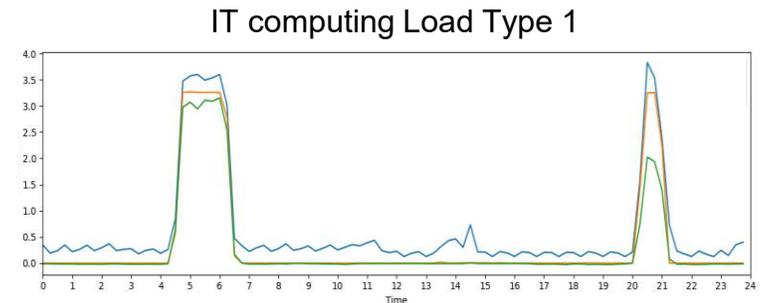
The load profiles are for illustration only

# Behind-the-meter load Identification



Roof-top Solar
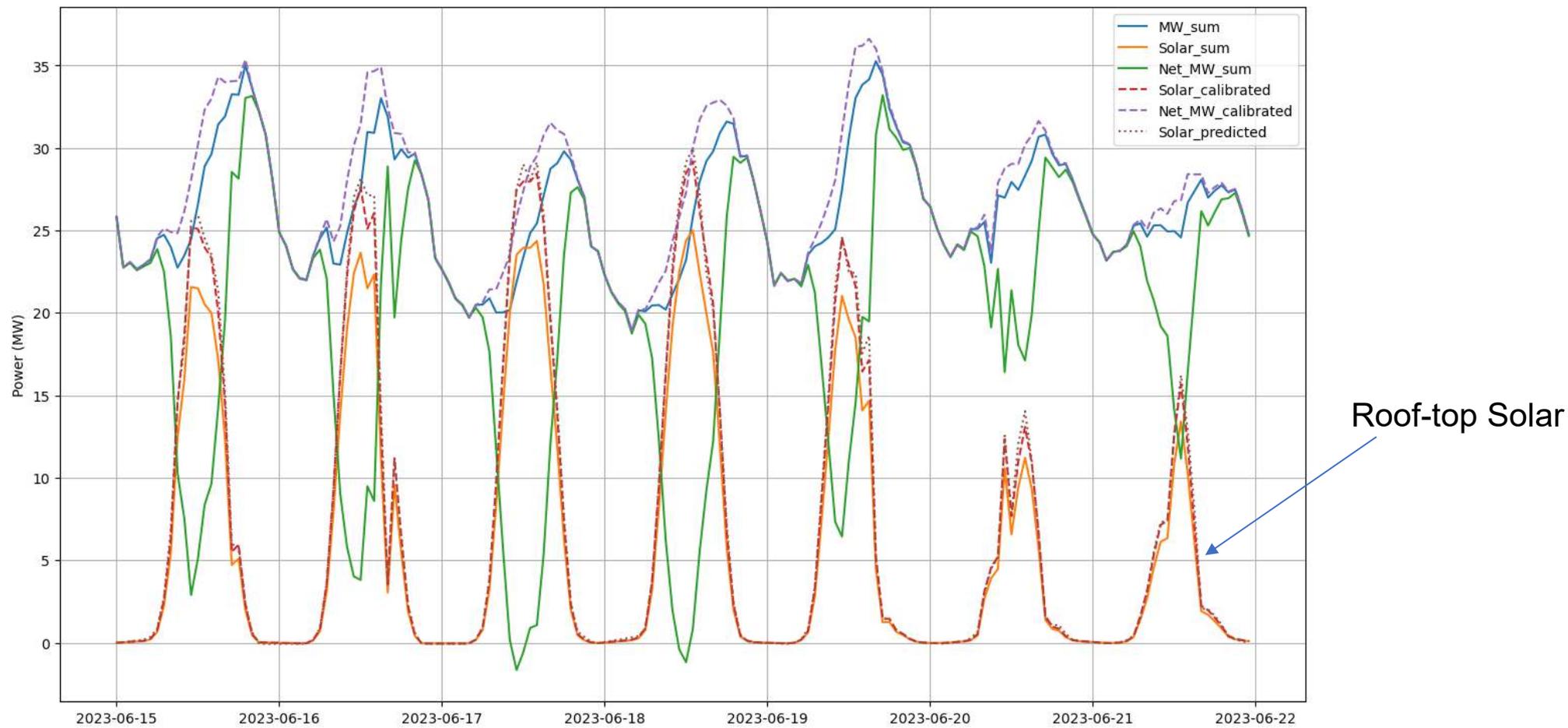
# Conclusions

- Data centers require **dedicated modeling approaches** due to their unique load composition and operating characteristics

- **Data-driven digital twin models** are essential to enable scalable, high-fidelity representation

- Modeling should **capture day-to-day operational dynamics**, rather than static or snapshot-based behavior

- **Modular model** designs are needed to flexibly address diverse data center architectures and use cases

- **Seamless integration** with large-scale power system models is critical for assessing grid interconnection and system-level impacts