



Reliability & Stability of Large IBRs and Large-Load Sites

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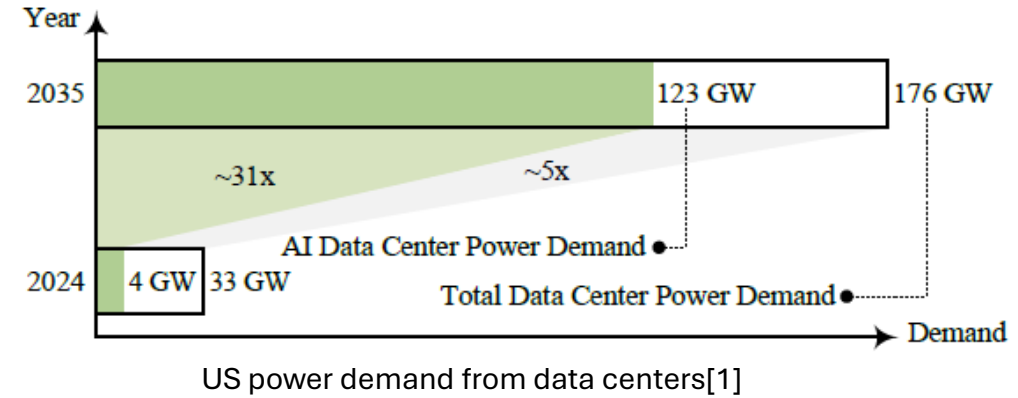
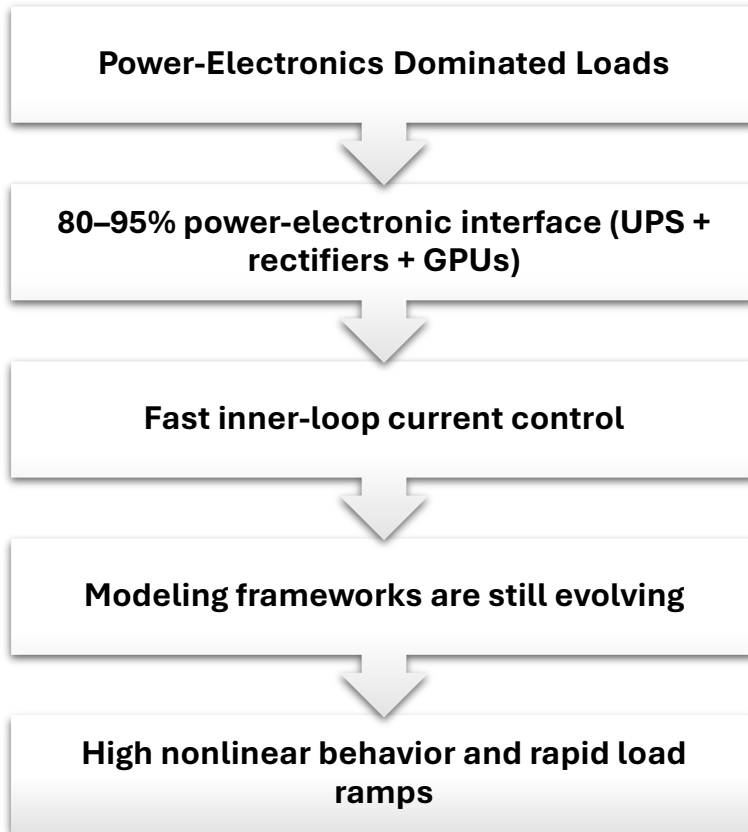
Agenda

- **Power system with IBRs and large loads**
- **Power system oscillation**
- **Oscillation screening methods**
- **EMT validation & case studies**



Rapid Shift in Grid Dynamics

❑ Large loads behave like IBRs



❑ Why stability challenges are increasing in systems with high penetration of IBRs & large loads

- Reduced System Inertia
- Voltage and Frequency Regulations Issues
- Forced oscillations
- Control interactions
- Limited Fault Current Contribution
- Protections and Control Interactions
- Gaps in Modeling Accuracy

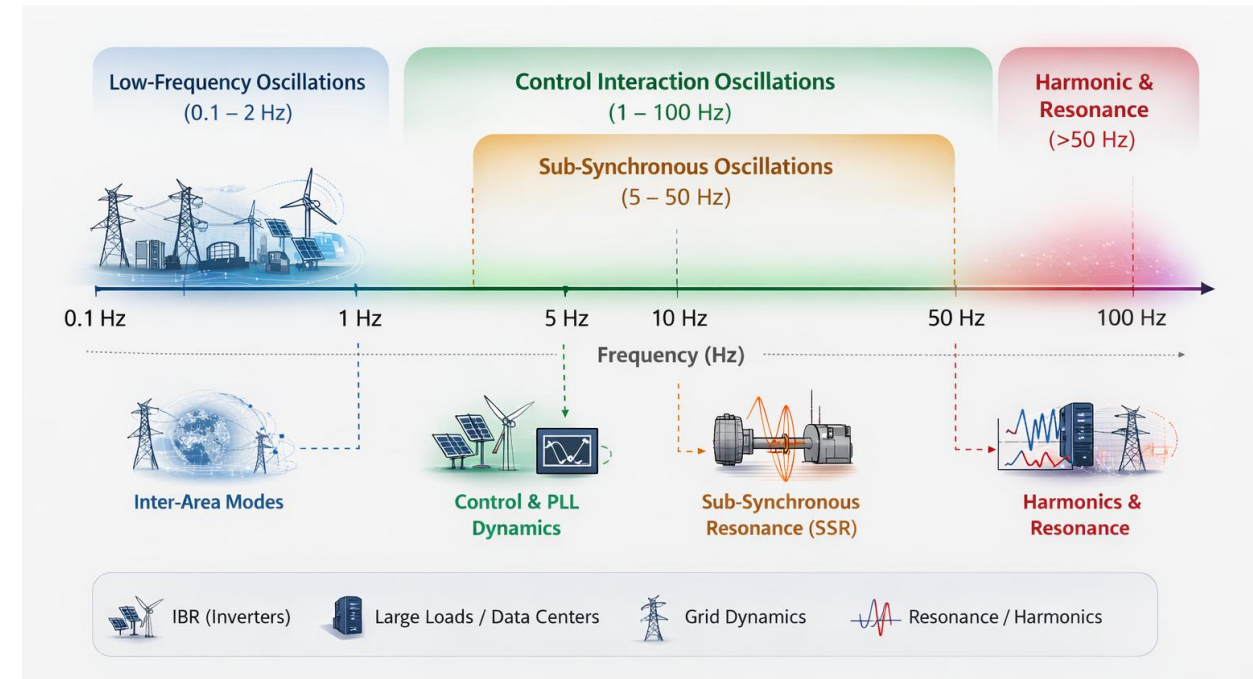


Oscillation Types in IBR + Large Load Systems

□ Oscillations in IBR & large-load systems can be grouped

into:

- Low-Frequency Oscillations (0.1–2 Hz)
- Sub-Synchronous Oscillations (5–50 Hz)
- Control Interaction Oscillations (1–100 Hz)
- Harmonic & Resonance-Based Oscillations (>50 Hz)





Oscillations Classification in IBRs and Large Load-Dominated Network

❑ Systemic Oscillations

- Occur mostly when a collection of power system elements are negatively damped
- Sensitive to grid strength, more prominent in weak grid condition
- Oscillation magnitude can grow for a sustained period

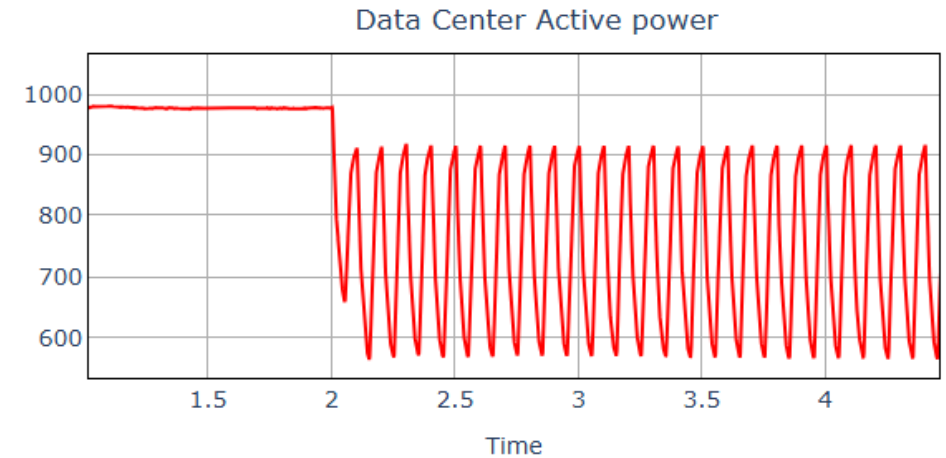
❑ Forced Oscillations

- Majorly caused by a single source
- Occur at specific frequencies
- Can appear in strong systems
- Growth may be bounded

❑ Example:

Oscillation Mechanism

- AI workloads create repeated power cycles.
- Typical oscillation frequency: 0.1 – 20 Hz.
- These fluctuations can excite natural system modes.



A 10 Hz forced oscillation leading to ~300 MW swing in the data center active power

❑ Remarks:

- ✓ Forced oscillations may excite natural frequencies of the system, including torsional modes of electrically close synchronous machine



Oscillation Screening Methods

□ State-Space Model Method

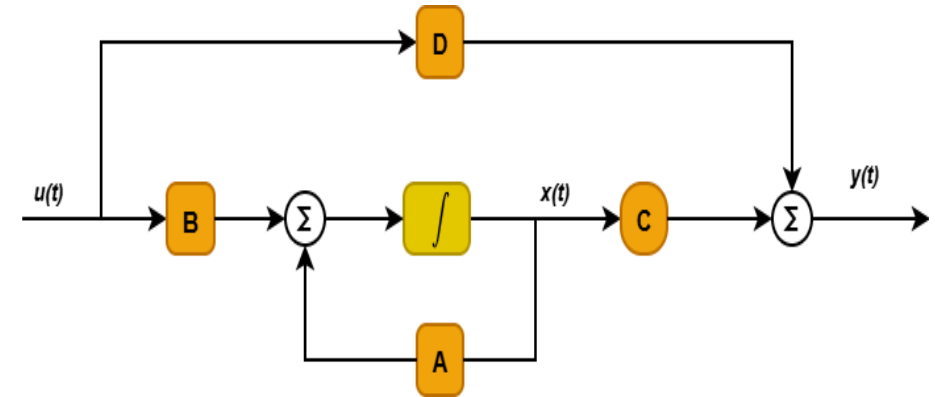
- Requires the differential equations that describe the behavior of the system.
- Suitable to small system where its full dynamics is well known

□ Eigenvalue Analysis

- Uses the eigenvalue (λ) of the state matrix to determine the oscillatory modes of the system.

□ Modal Analysis

- Investigate mode shape (participation factor) of each state



□ Drawbacks

- Developing the state matrix is cumbersome and non-trivial
- Difficulty to accurately represent the black-boxed OEM IBR models
- Standardized Large Models



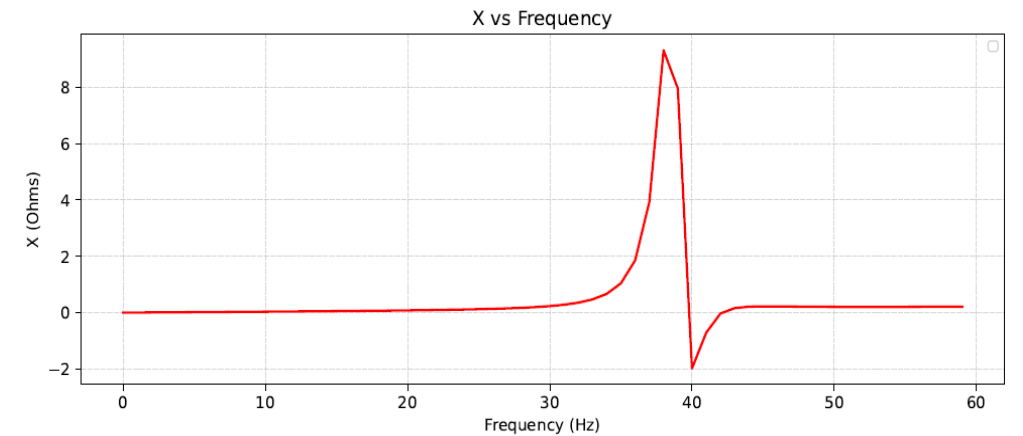
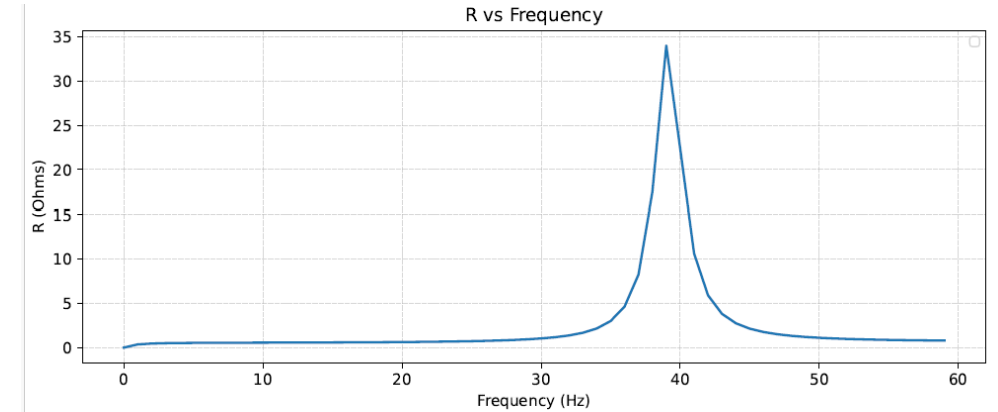
Oscillation Screening Methods

❑ Passive Frequency Scan

- Models the network using R, L, C representations
- Provides the frequency-dependent characteristics of the network
- Calculates the network impedances and finds the electrical resonance(s) over a spectrum of frequencies

❖ Drawbacks

- Does not capture control-induced negative damping which is inherent in IBRs and Data center loads





Oscillation Screening Methods

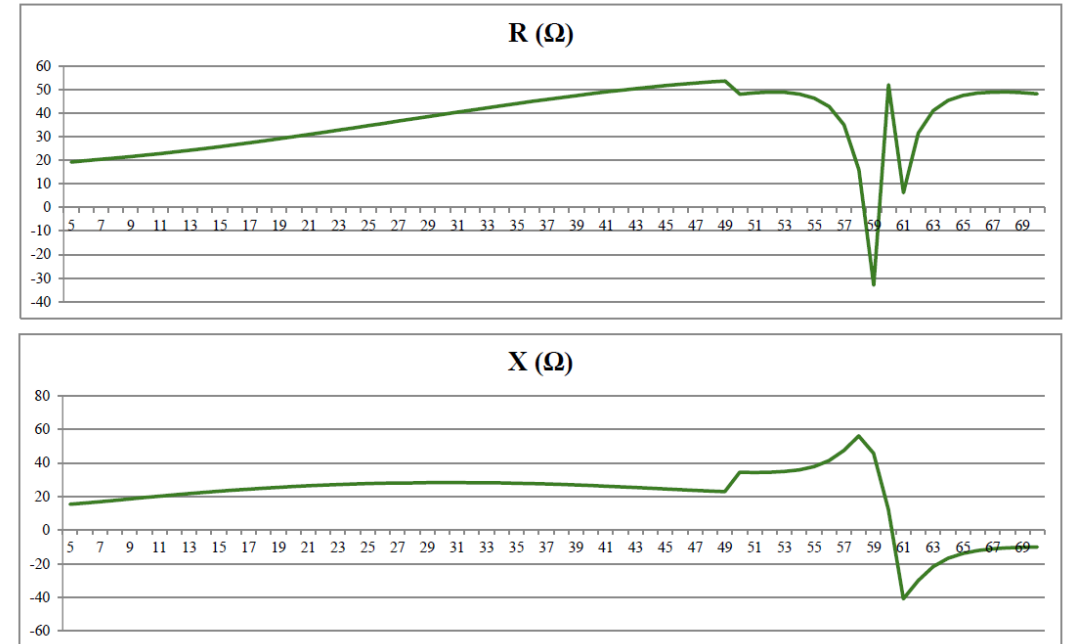
Dynamic Frequency Scan

- Captures the frequency-dependent impedance including control dynamics
- Performed by injecting series voltage perturbations or shunt current perturbations
- Can identify negative damping introduced by IBR control loops

Drawbacks

- Result is dependent on magnitude of perturbation
- Can be time-consuming for large detailed-EMT models

Active Frequency Scan of PNNL's Distributed Data Center Model (R and X Plots)





Recommended Study Workflow

❑ Step 1: Passive Scan (R-L network)

- Quick scan of network impedance (e.g. PSCAD frequency sweep with converters as short-circuits) to identify major resonances.

❑ Step 2: Dynamic Scan (include IBR controls)

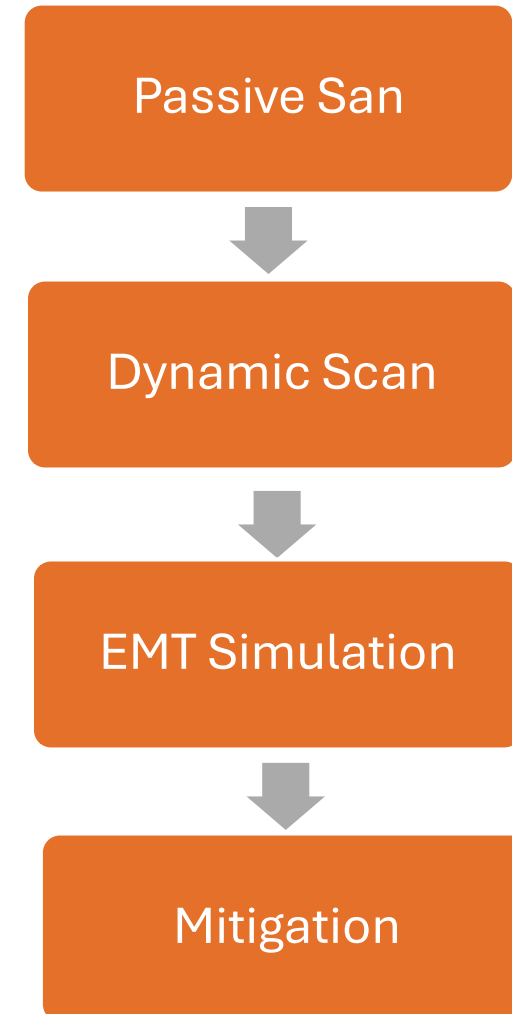
- Inject at IBR terminals to capture negative-damping regions (shows potential unstable modes from control loops).

❑ Step 3: EMT Simulation

- Model the detailed system (with full EMT IBR models) and apply worst-case disturbances (load cycles, faults) to confirm which modes grow.

❑ Step 4: Tune/Mitigate

- Adjust control gains, add GFM-BESS or STATCOM, or change network (series cap limits) to damp identified modes.





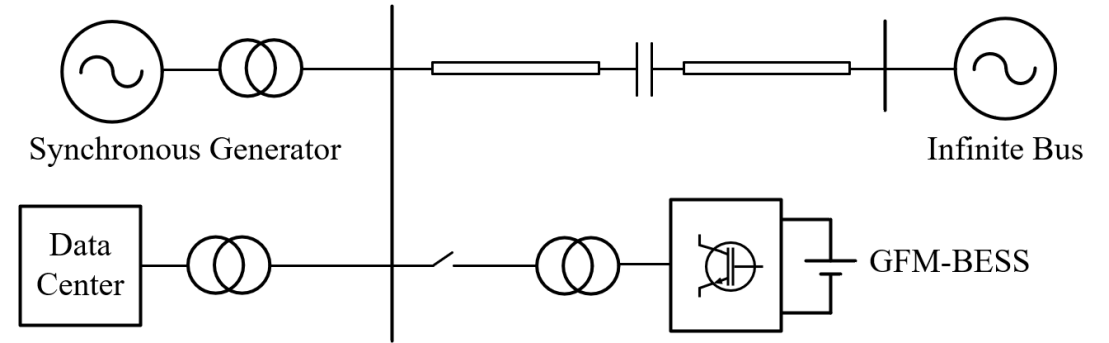
Case Study

Investigate whether AI data center load fluctuations can induce sub-synchronous oscillations.

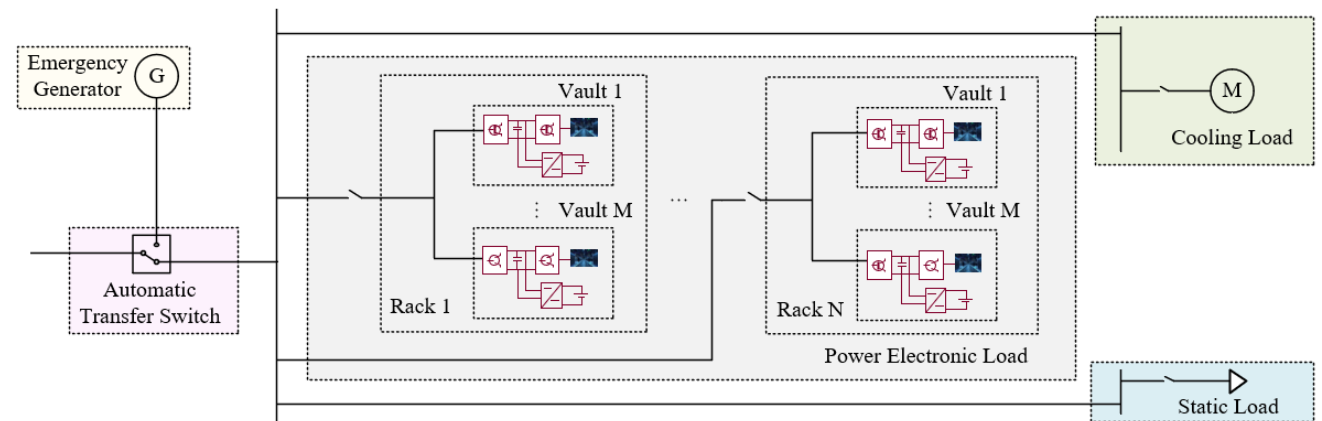
System configuration:

- Synchronous generator
- Series-compensated line
- Data center
- GFM-BESS

PSCAD EMT model



The IEEE benchmark for sub-synchronous resonance



The structure of a data center facility.



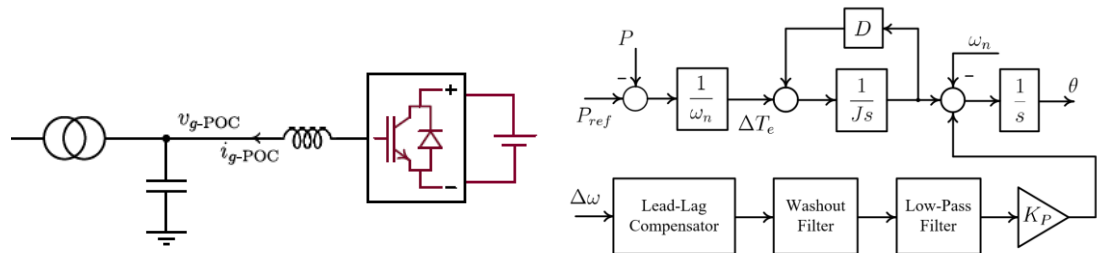
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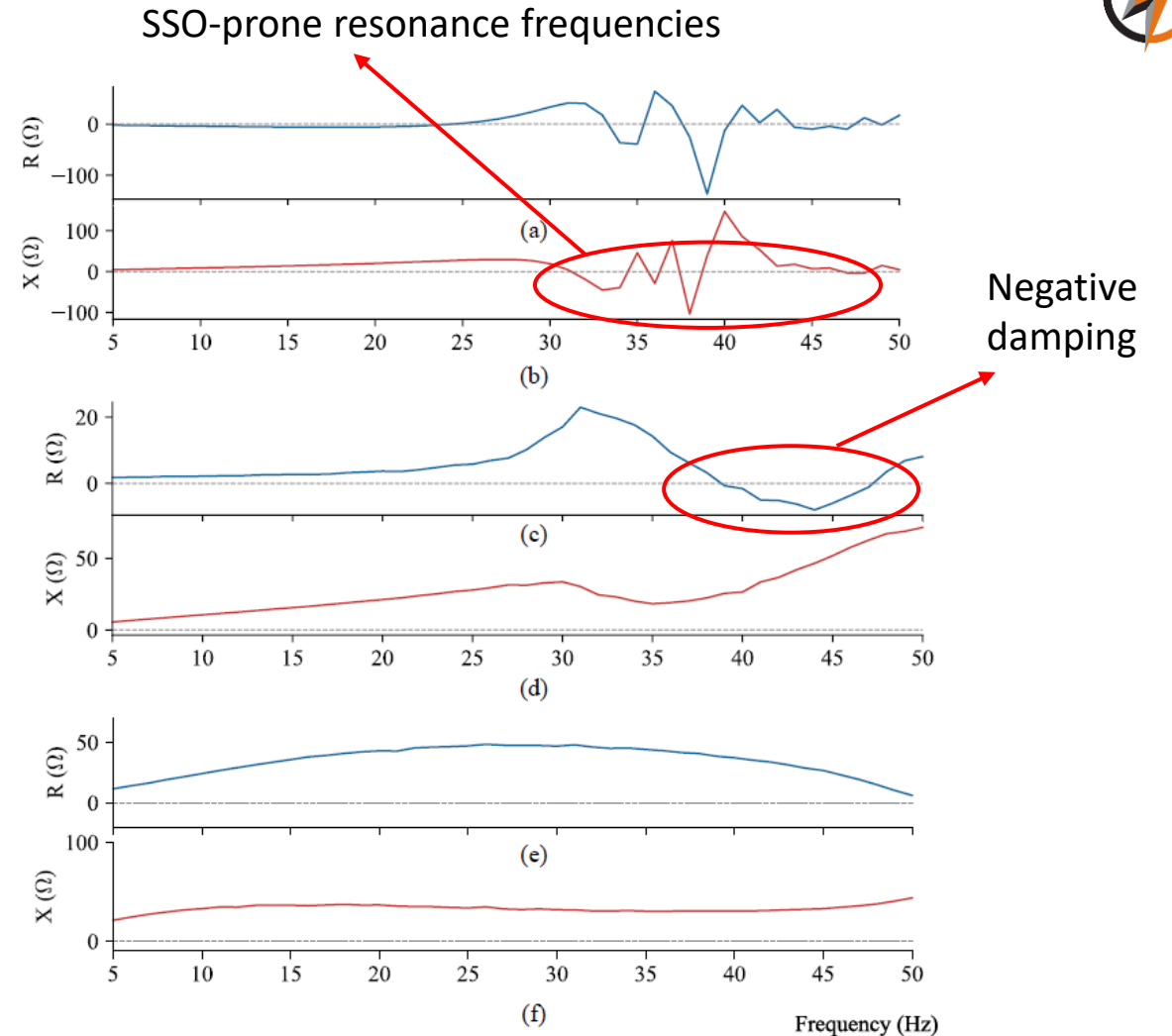
System configuration:

- Synchronous generator
- Series-compensated line
- Data center
- GFM-BESS

PSCAD EMT model



The control structure of a VSM-controlled GFM-BESS augmented with a POD



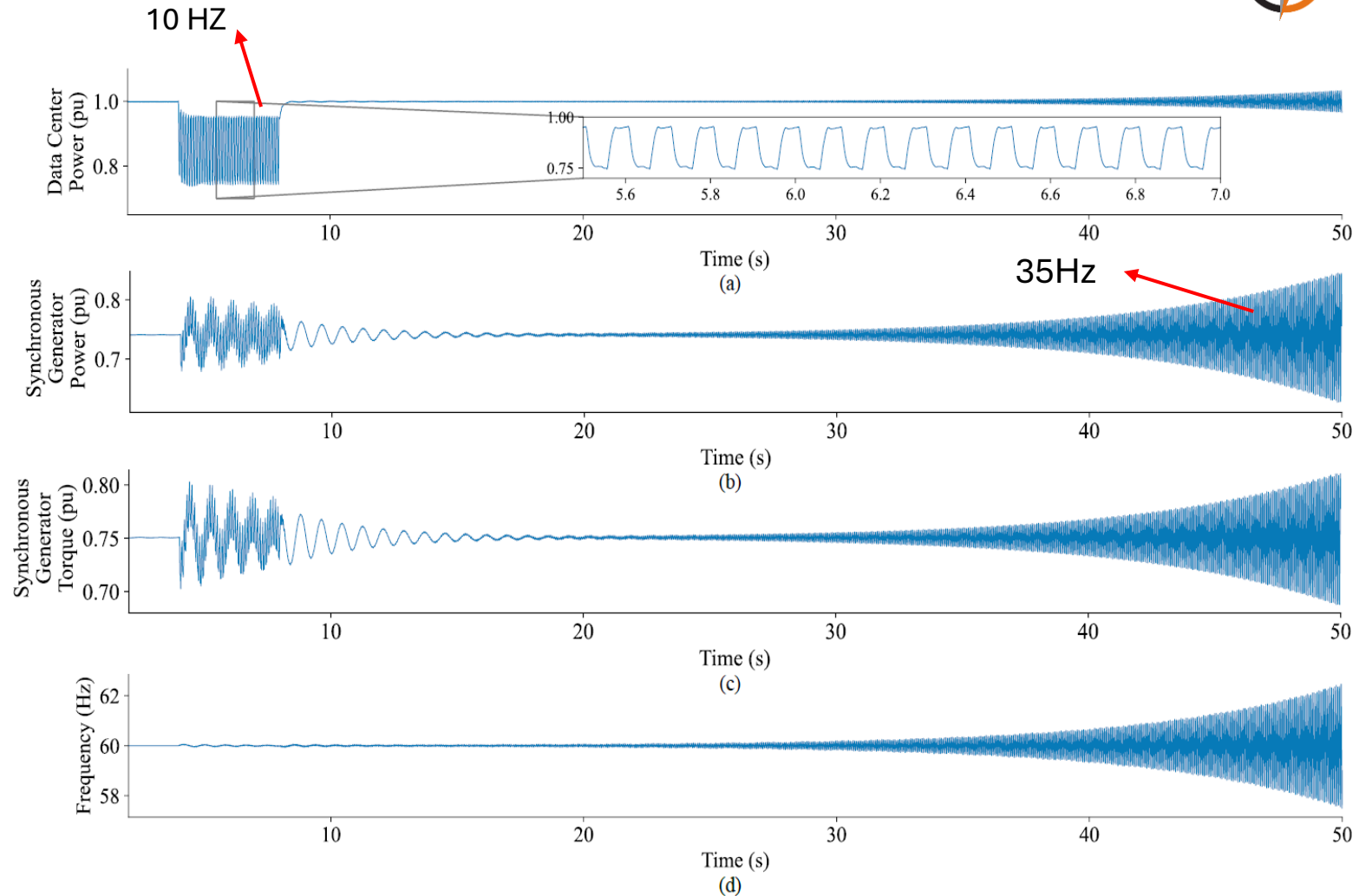
Frequency scan results for the components of the test system
(a) and (b) System's passive frequency scan;
(c) and (d) Data center's active frequency scan;
(e) and (f) Active frequency scan of the data center co-located with GFM-BESS.



Case Study

- ❑ GFM-BESS is out of service
- ❑ load starts oscillating at 10 Hz between 750 MW and 950 MW for 4 seconds
- ❑ **Without mitigation:**
 - Sustained oscillations observed
 - The load fluctuation, excite the natural frequency of a network
 - Generator power oscillations increase over time (33 Hz)

This confirms that large electronic loads can excite poorly damped modes.



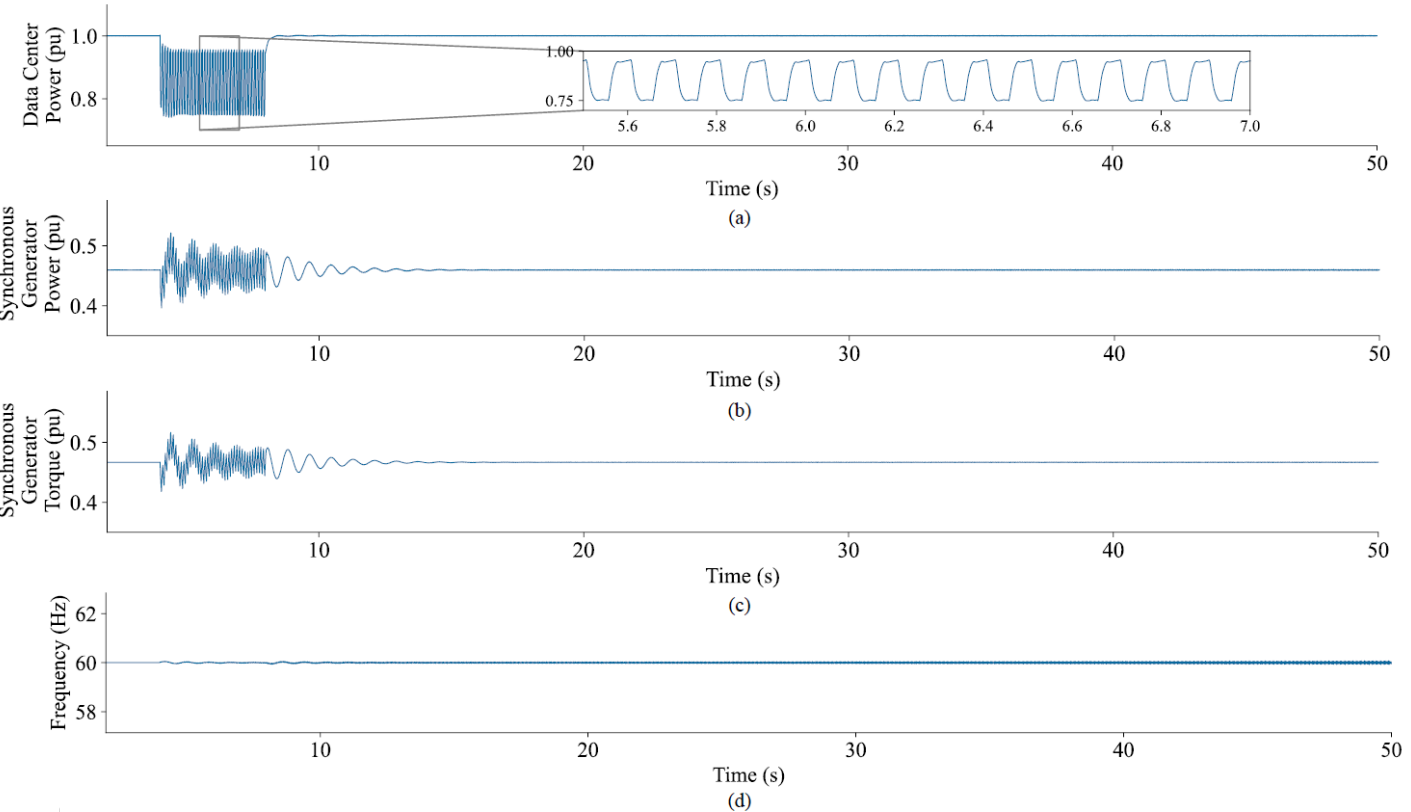
(a) Data center power, (b) Synchronous generator power, (c) Synchronous generator torque, (d) Frequency



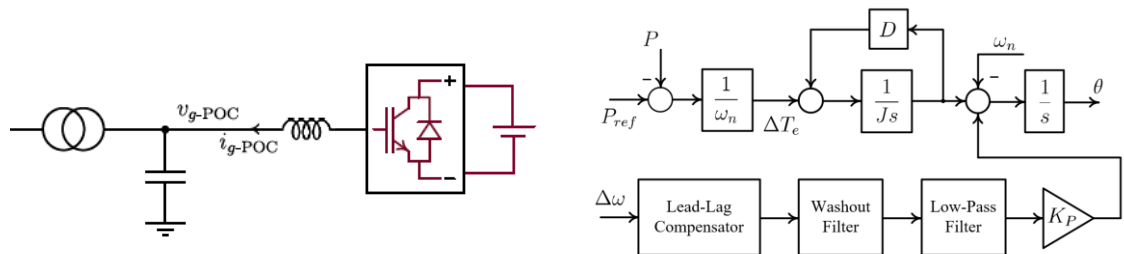
Case Study

With mitigation:

- GFM-BESS is out of service
- load starts oscillating at 10 Hz between 750 MW and 950 MW for 4 seconds
- the GFM-BESS with POD improves system robustness under data-center-induced disturbances



(a) Data center power, (b) Synchronous generator power, (c) Synchronous generator torque, (d) Frequency



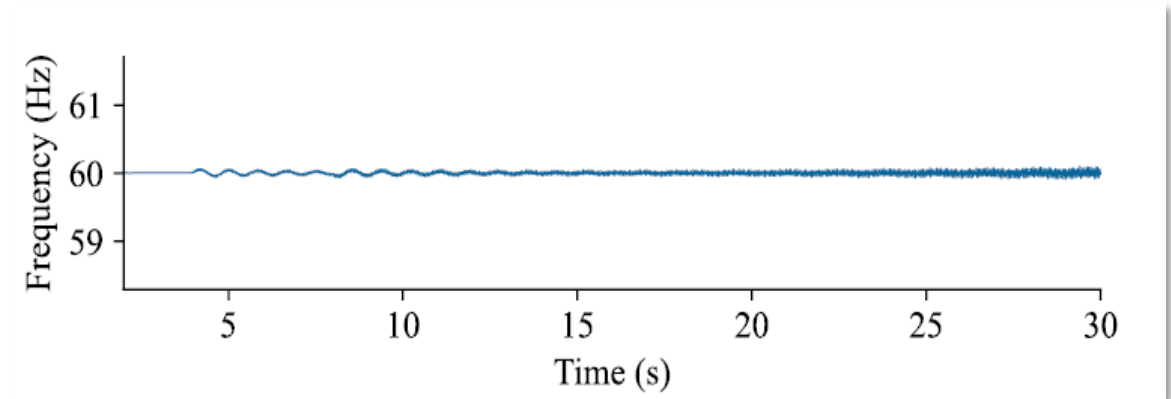
The control structure of a VSM-controlled GFM-BESS augmented with a POD



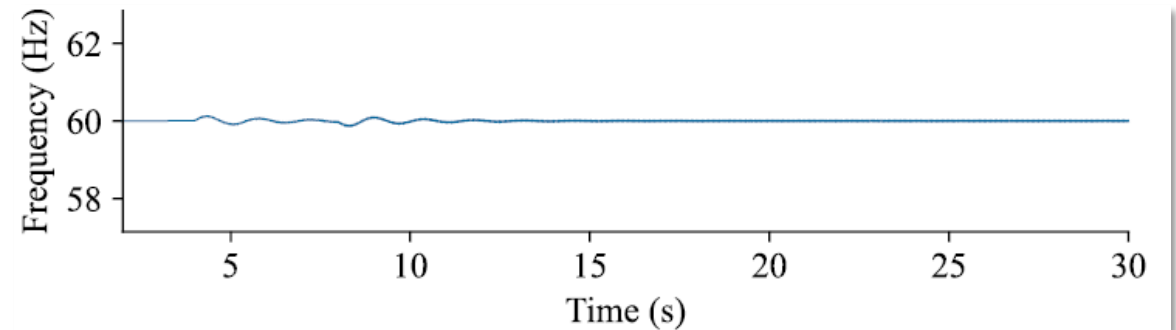
Case Study

□ Mitigation with STATCOM:

- STATOM with POD
- Load oscillates at ~10 Hz between 750–950 MW for 4 s
- At $t = 50$ s, frequency varies 59.6–60.4 Hz
- With GFM-BESS, frequency varies only 59.97–60.03 Hz
- Better damping with GFM due to inherent damping (constant D) plus POD



With STATCOM and POD



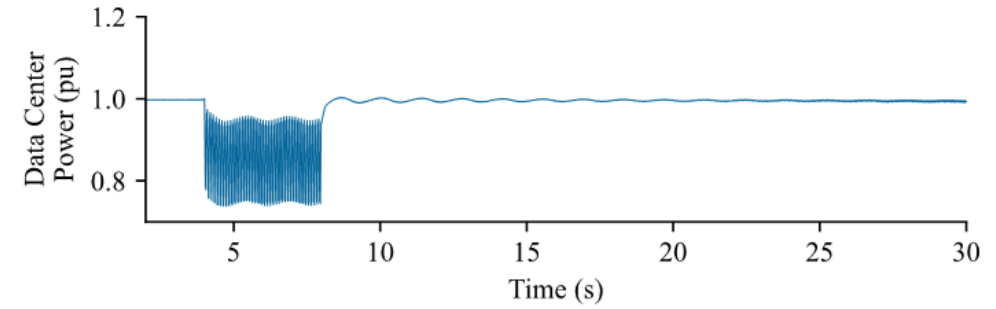
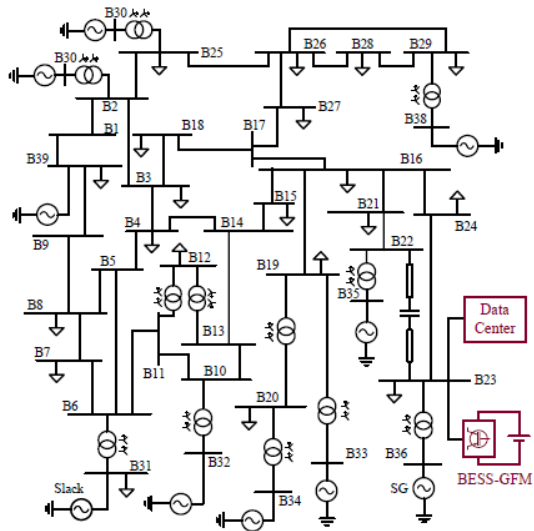
With GFM and POD



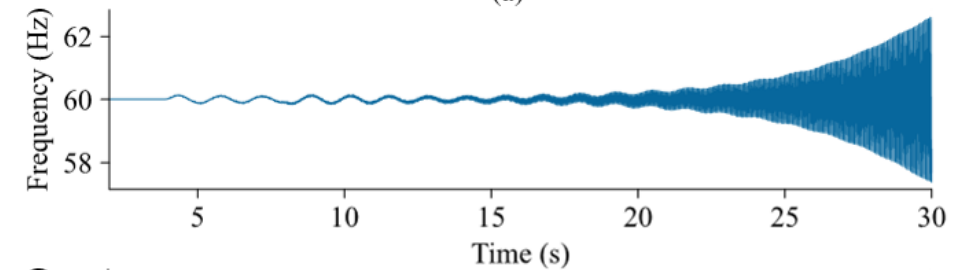
Case Study 2

Project example:

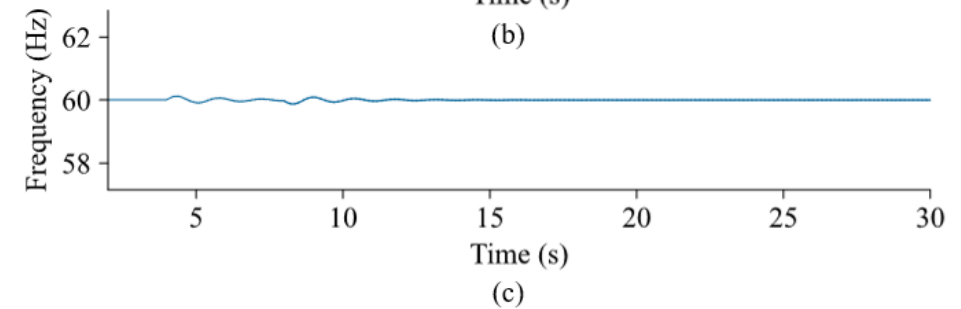
- IEEE 39-Bus system with Series Cap between bus 22 & 23
- Collocated BESS & Data center at bus 23
- Line B24-23 out, Load oscillates at ~10 Hz between 750–950 MW for 4 s



(a)



(b)



(c)

(b) GFM is out of service and (c) GFM-BESS is in service.



Takeaways

- ❑ Large electronic loads behave like converters and can introduce new oscillation modes, therefore early screening is critical.
- ❑ Frequency-sweep impedance scans identify weak damping early and often predict modes later confirmed by EMT studies.
- ❑ When risks are detected, detailed EMT simulations are required to validate limits and design mitigation measures.
- ❑ GFM inverters enhance damping and system resilience, supporting secure integration of large AI/data-center loads in low-inertia grids.



THANK YOU!

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