NREL

Data Center Power System: Architectures and Modeling Considerations

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Photo by Josh Bauer / Bryan Bechtold, NREL 82067

Outline

- Factors Impacting Data Center Modeling for Grid Studies
- Datacenter Power System Architecture
  – Typical and new
  – Modeling considerations
- Small-Signal Stability
  – Impedance-based stability analysis and specifications
- Megawatt Scale Demo at NREL
  – Torsional oscillations in a 2.5 MVA generator thru load profile emulation

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Factors Impacting Data Center Modeling for Grid

Architecture of Data Center Power System

Power Delivery (from POI to IT Racks)

- AC UPS
- DC UPS
- SST
- Side Car
- Non-IT Loads

IT Racks (from Rack to GPUs/CPUs)

- Rack Busbar Voltage
  - 48 Vdc
  - 800 Vdc
  - ±400 Vdc
- PSU
  - Single-phase PFC (single-boost, double-boost, bridgeless)
- BBU
- CBU

Model Applications

- Load Profile
  - Torsional Modes, Flicker
- Transient Behavior
  - Loss of Load, LVRT
- Dynamic Interactions
  - Low Frequency
  - High Frequency

***UPS**: Uninterruptible Power Supply*
***PSU**: Power Supply Unit*
***BBU**: Battery Backup Unit*
***CBU**: Capacitor Bank Unit*
***SST**: Solid-State Transformer*

Various impedances in the data center building distribution network and aggregation of power converters play an important role in the model development.

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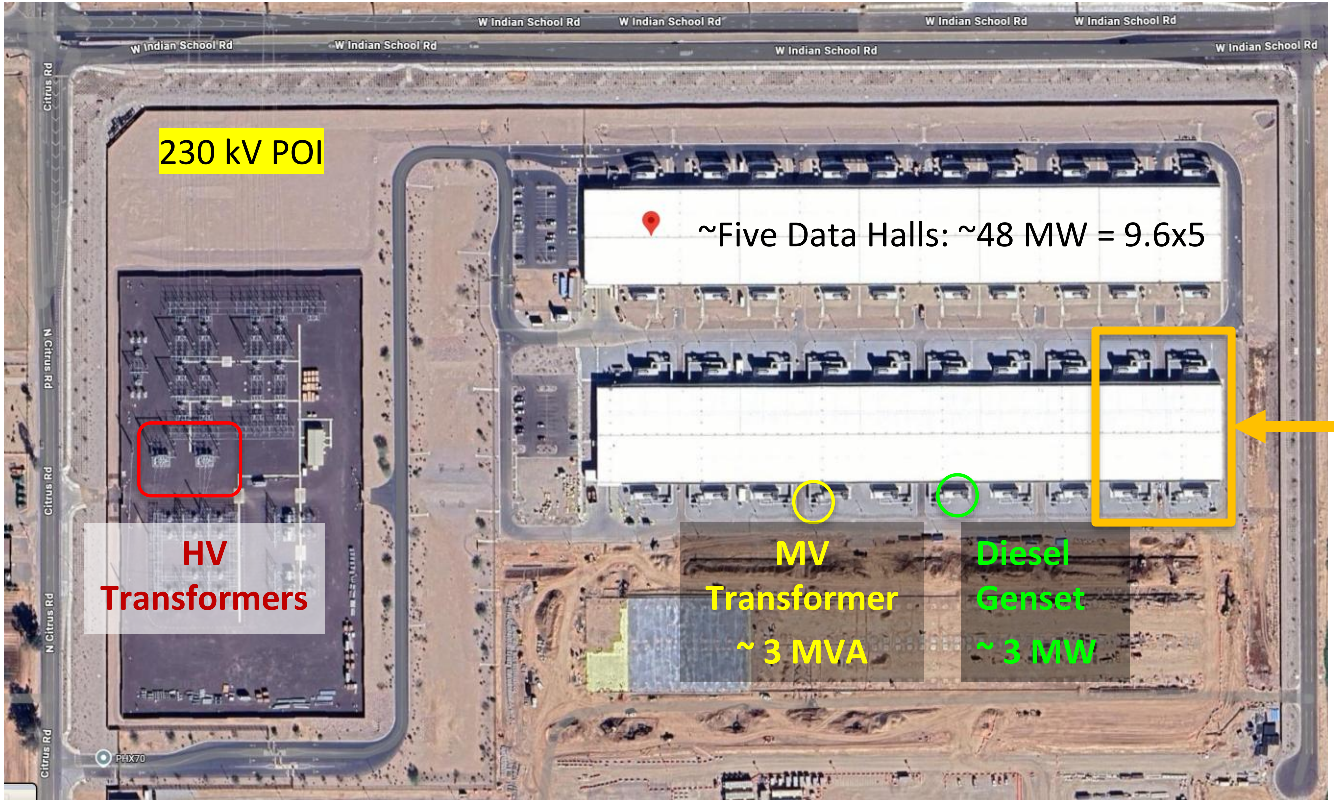
Architecture of Data Center Power System

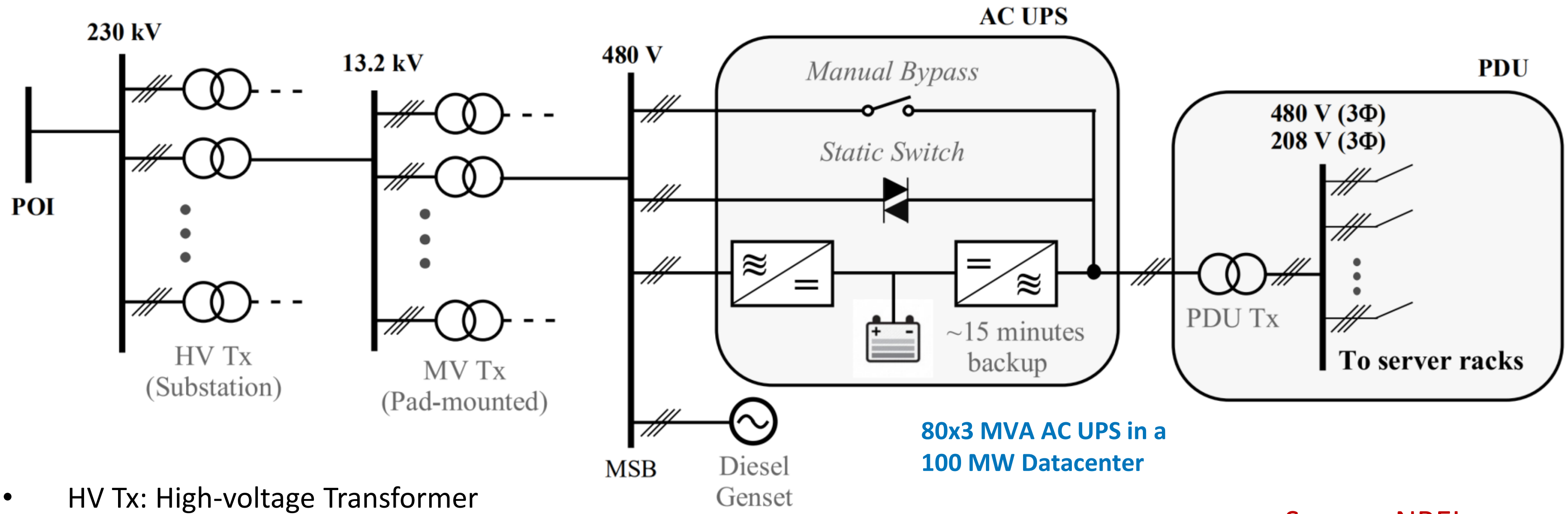
Data Center Near Phoenix, AZ (~100 MW)



- Each building is estimated to have five data halls with around four pods per data hall
- Each pod is estimated to have 2.5 MW of load
- Each pod has one Genset, two AC UPS, and numerous IT server racks

Image Source: Google Maps

Typical Architecture: From POI to Server Racks



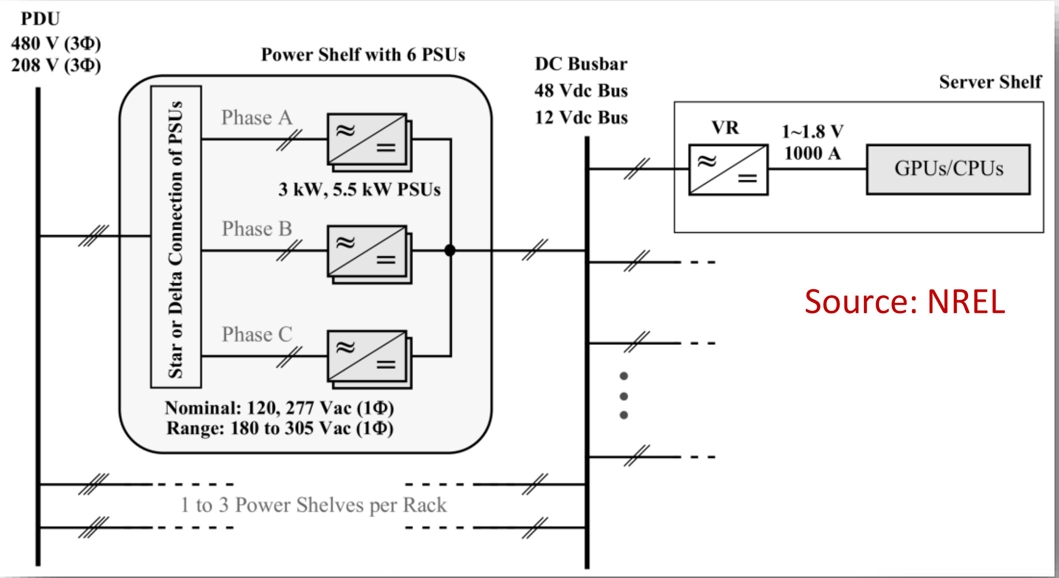
80x3 MVA AC UPS in a 100 MW Datacenter

40x3 MVA Genset in a 100 MW Datacenter

Source: NREL

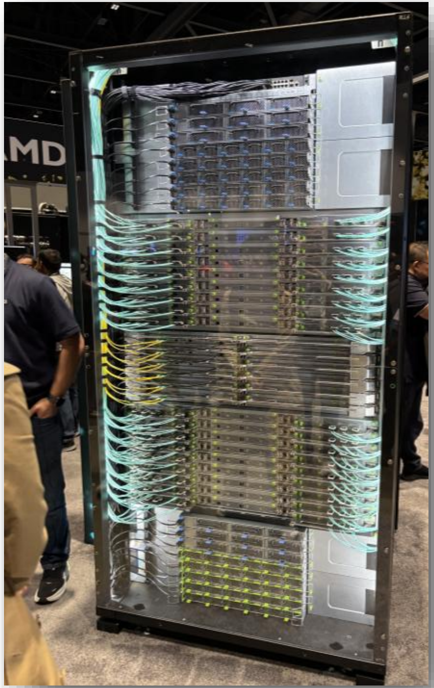
- HV Tx: High-voltage Transformer
- MV Tx: Medium-voltage Transformer
- MSB: Main Switch Board
- UPS: Uninterruptible Power Supply
- PDU: Power distribution Unit
- PDU Tx is not always required

Typical Architecture: Inside Server Racks



Source: NREL

Approx. 300 kW Rack



3.6 kW PSU

5.5 kW PSU

Two 33 kW Power shelves each with 6 PSUs (2 x 6 x 5.5 kW)

Photos by S. Shah (NREL)

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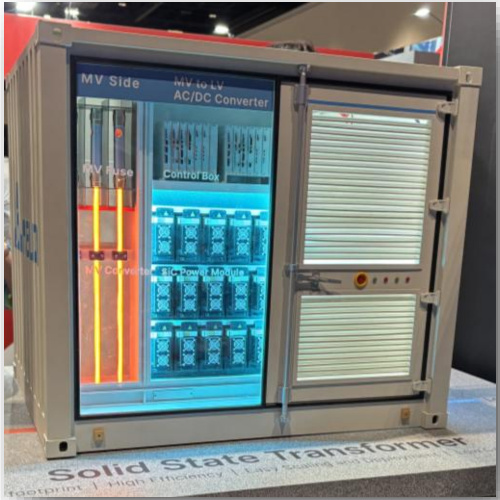
New Architectures: 800 Vdc Racks and Power Delivery

Power Delivery

Solid State Transformer (SST)
MVAC to 800 Vdc
(Conceptual photo)



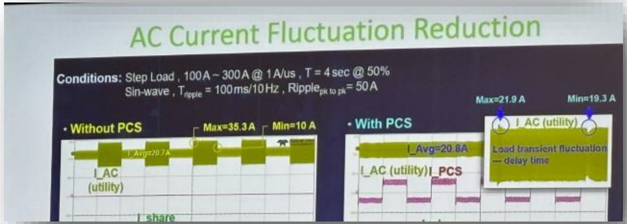
Photos by S. Shah (NREL)

Server Racks

Power shelves w/ 6x30 kW PSUs

Battery Bank Unit (BBU)

Capacitor Shelf for Load Smoothing



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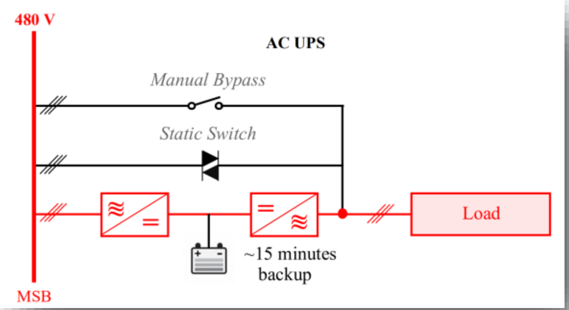
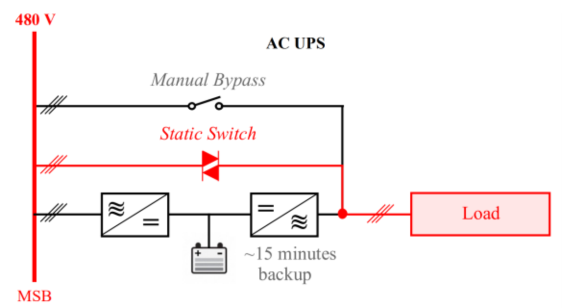
Impact of AC UPS Operation Modes on Modeling



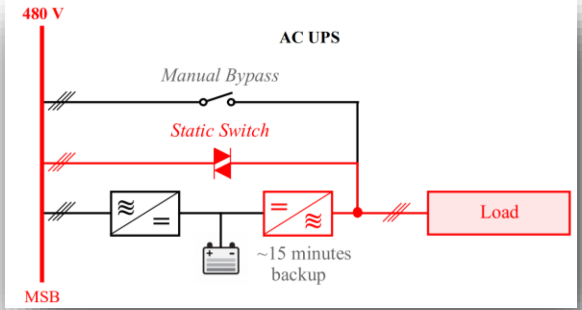
Double Conversion Mode

- Highest Controllability of Power Quality
- Relatively Low Efficiency: ~95 %



Bypass Mode

- No Controllability of Power Quality
- Highest Efficiency: ~99.6 %



Single Conversion Mode (Not Common)

- High Power Quality
- High Efficiency: ~99.2 %

In the bypass mode, the grid does not see the dynamics of AC UPS – its modeling can be simplified to include only the voltage ride-through profile, e.g., ITIC curve.

Summary

- Two types of power converters in data centers generally interact with the grid:
  - AC Uninterruptible Power Supplies (AC UPS)
    - 10s to 100s of AC UPS, each rated at few megawatts, are present in a large datacenter
    - AC UPS interacts with the grid only if it is operated in the double-conversion mode
    - Models are very similar to IBRs as the front-end of AC UPS is a three-phase voltage source converter
  - Power Supply Units (PSU)
    - 100s of 1000s of PSUs, each rated at few kilowatts, are present in a large datacenter
    - PSUs interact with the grid only if the AC UPS is not operated in the double conversion mode
    - Models are very different from IBRs as the front-end is single-phase PFC converters. Few different topologies are commonly used for single-phase PFCs.
    - It is important to properly aggregate 1000s PSUs in the model while properly considering various impedances of the distribution network between the POI and IT racks.
- New technologies (e.g., BBU, CBU, SST, and side car) and new architectures (e.g., 800 Vdc, ±400 Vdc) can significantly alter the model structure and requirements.

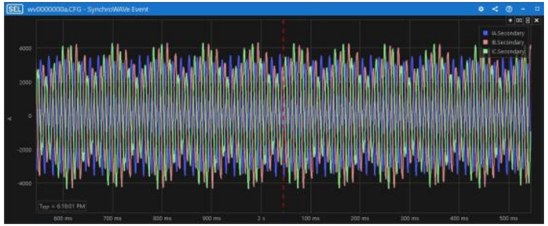
Small-Signal Stability

Subsynchronous Oscillations, Control Interactions, Weak Grid Stability

Oscillations from Data Centers

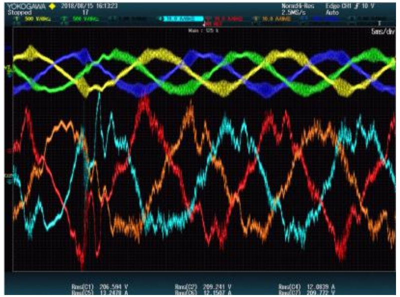
Oscillations in a Meta Data Center in 2018

11 Hz



Source: J. Sun, et. al, CSEE Journal of Power and Energy Systems, 2022.

5-10 kHz

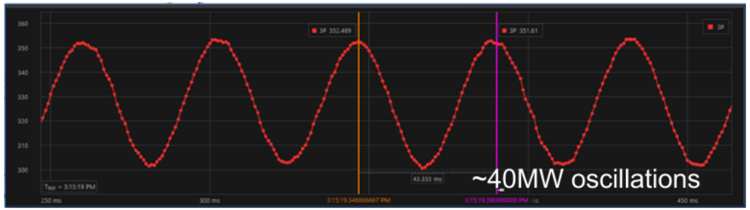


Source: J. Sun, et. al, CSEE Journal of Power and Energy Systems, 2022.

The problem was resolved in 2020. Meta has developed impedance-based specifications to avoid this issue.

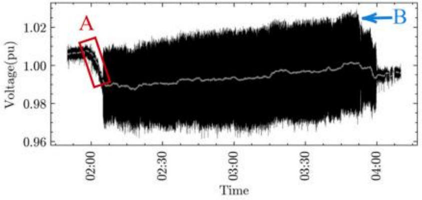
Grid-Level Oscillations from Data Centers

ERCOT Grid



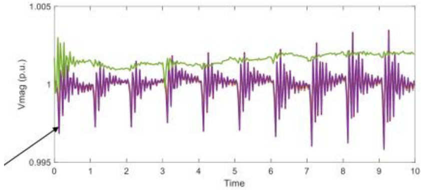
Source: ERCOT

Dominion Energy



14.7 Hz

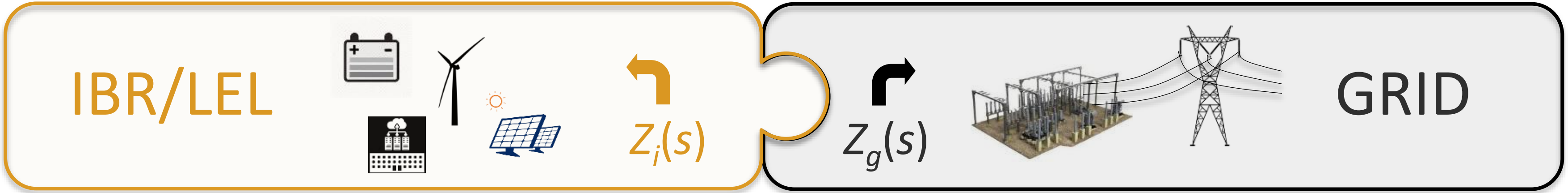
Source: C. Mishra, et. al. (Elsevier 2025)



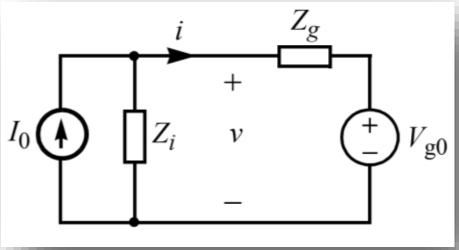
11 Hz

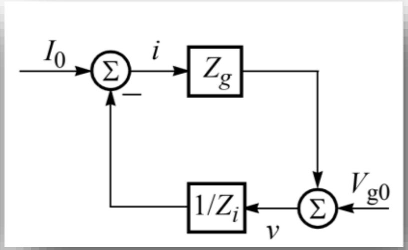
Source: EPRI, https://www.epri.com/events/539b60d7-57da-4252-9968-fb1754ee3b66

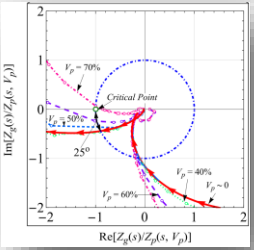
Impedance-Based Stability Analysis

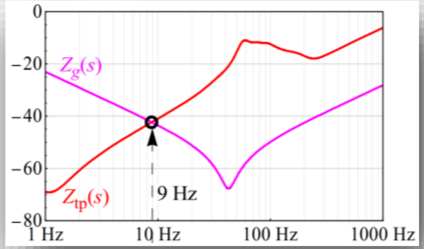


- **Loop Gain**: $Z_g(s)/Z_i(s)$
- **Pre-requisite:**
  - *Standard Criterion*: IBR and the Grid are Separately Stable
  - *Reversed Criterion*: IBR and the Grid are Stable when Interconnected





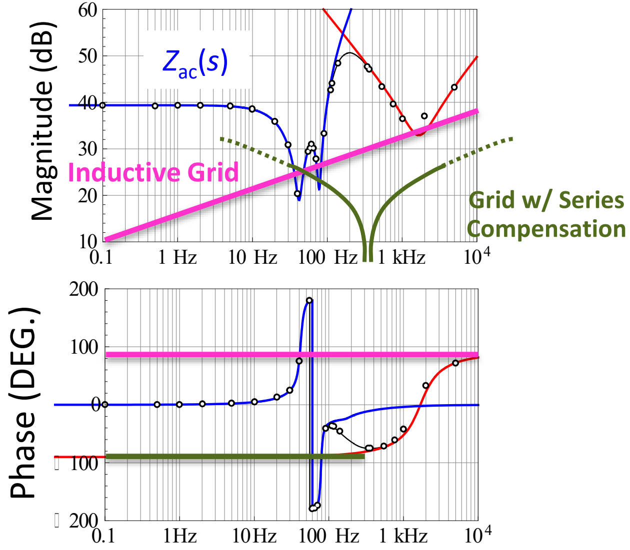




Mechanism of Control Interactions in Data Centers

- Impedance of Single-Phase VSC

$$Z_{ac}(s) \approx \left\{ \frac{1}{sL + V_{dc}H_i(s)} - \frac{j}{2} I_1 [T_p(s - j\omega_1) - T_n(s + j\omega_1)] \right\}^{-1}$$

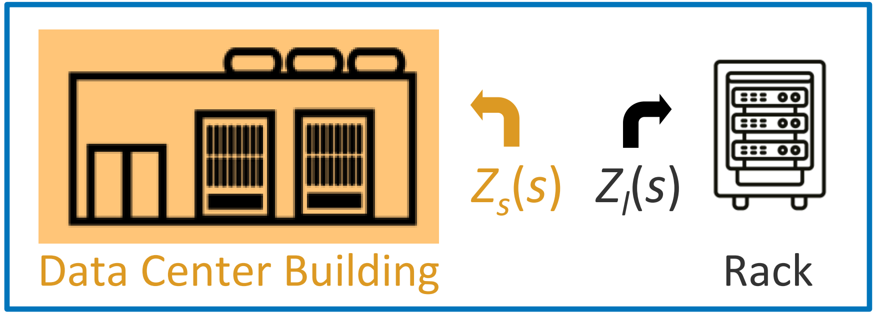


- Impedance of single-phase VSCs (such as PSUs) has two dips around the fundamental frequency and it exhibits negative damping
  - These dips can interact adversely with inductive or capacitive impedance of the source (grid + distribution network) and potentially create low-frequency oscillations
  - The distance of the dips from the fundamental frequency is correlated with the bandwidth of outer control loops (V_{dc} control, PLL, etc.).

Impedance-Based Specifications from Meta

- Base Impedance Ratio (BIR) is the ratio of PSU base impedance (V^2/P) to building impedance ($2\pi f_1 L_s$)
  - It is equivalent to grid Short-Circuit Ratio

$$BIR = \frac{V^2}{P} \cdot \frac{1}{2\pi f_1 L_s}$$



- Building Requirement: Must be designed to have high BIR

BIR at Rack Terminal	Conclusion
> 2.5	Pass
2.0 to 2.5	Marginal Pass
1.5 to 2.0	Marginal Fail
< 1.5	Fail

- PSU Requirement: Must be stable with low BIR

Min. BIR Reqd. for Stability	Conclusion
> 2.0	Fail
1.5 to 2.0	Marginal Fail
1.0 to 1.5	Marginal Pass
< 1.0	Pass

Reference: Melaku Mihret, OCP Summit 2020

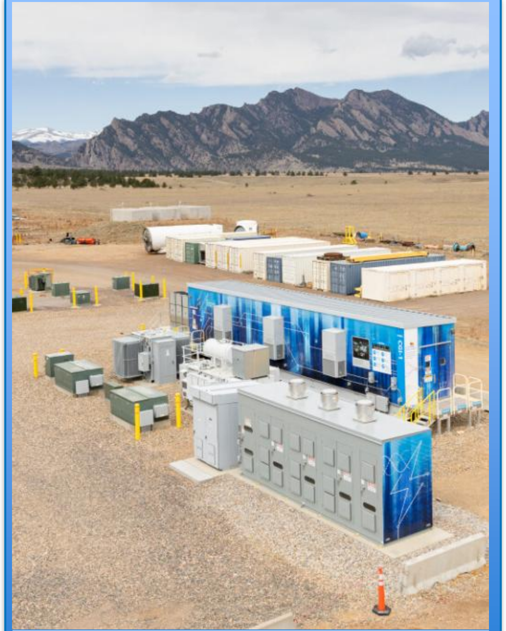
Megawatt-Scale Demo at NREL

Torsional oscillations in a 2.5 MVA generator because of a data center load profile emulate by a 7 MW grid simulator.

Emulation of Data center Load Profile

- A 7 MW grid simulator is used to emulate fast dynamic load profile of a datacenter
- A 2.5 MVA synchronous generator is used to represent a conventional generation

2MW Synchronous Machine
GE Gas Turbine Controller
High Fidelity Gas Turbine Emulation



Fast load emulation using:
7MVA CGI1
30ms load ramps +-1MW
(faster possible)

Source: NREL

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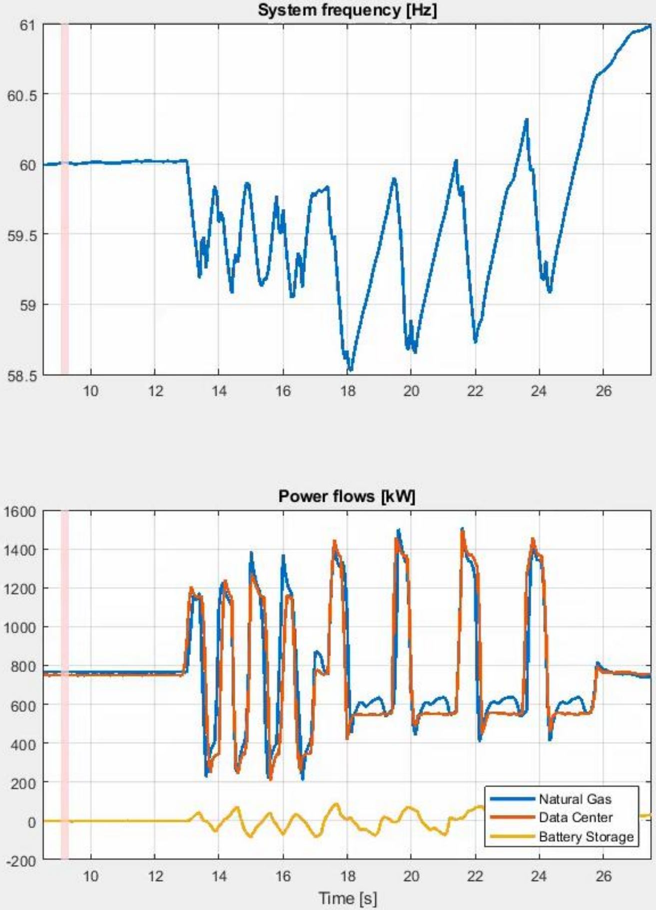
Impact of Load Fluctuations on Conventional Generation:
Without Hybridization – BESS Does Not Respond

ARIES by NREL



Natural Gas Generator Output (2.5 MVA Machine)

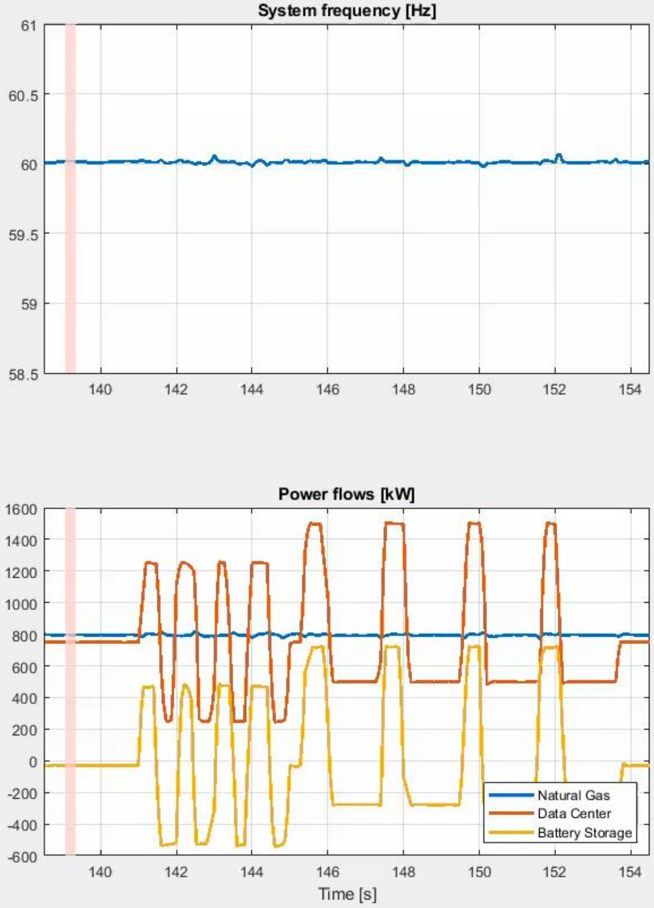
Datacenter Load (7 MW CGI)

Battery Energy Storage System (BESS) (1MW/1MWh)

Shaft video at 30fps With nominal 1800 RPM due to aliasing the video is still

Impact of Load Fluctuations on Conventional Generation:
With Hybridization – BESS Absorbs Load Fluctuations

Camera footage



Natural Gas Generator Output (2.5 MVA Machine)

Datacenter Load (7 MW CGI)

Battery Energy Storage (1MW/1MWh)

Shaft video at 30fps With nominal 1800 RPM due to aliasing the video is still

Summary

- When the synchronous generator supplied emulated data center load without any support from BESS, its shaft experiences large oscillations, as observed from the generator output frequency.
  - Such large variations in the speed of a conventional generator can result in fatigue-induced shaft failure

- The output of the synchronous generator remains almost flat when the fluctuations in the datacenter load profile are absorbed by BESS
  - This eliminates torsional oscillations in the conventional generator, thereby reducing risks of fatigue-induced shaft failure.
  - The effectiveness of a BESS in absorbing load fluctuations depends on the speed of load monitoring system, the control bandwidth of BESS, and its electrical distance from the load.

New Projects at NREL on Data Center Stability

- DOE-sponsored project for mitigating grid reliability impacts of data centers
  - EMT and phasor models of data centers
  - Stability analysis tools for data centers
  - Recommended performance guidelines
- Collaboration with power electronic equipment manufacturers for testing and optimizing the performance on both load and grid side.

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Thank you!

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