Data Center Power Systems

EMT Modeling for Evaluating Converter-Driven Stability Problems and Oscillations

Shahil Shah
Principal Engineer, NLR

ESIG Summer Workshop: Large Load Modeling, Testing, and Interconnection Requirements

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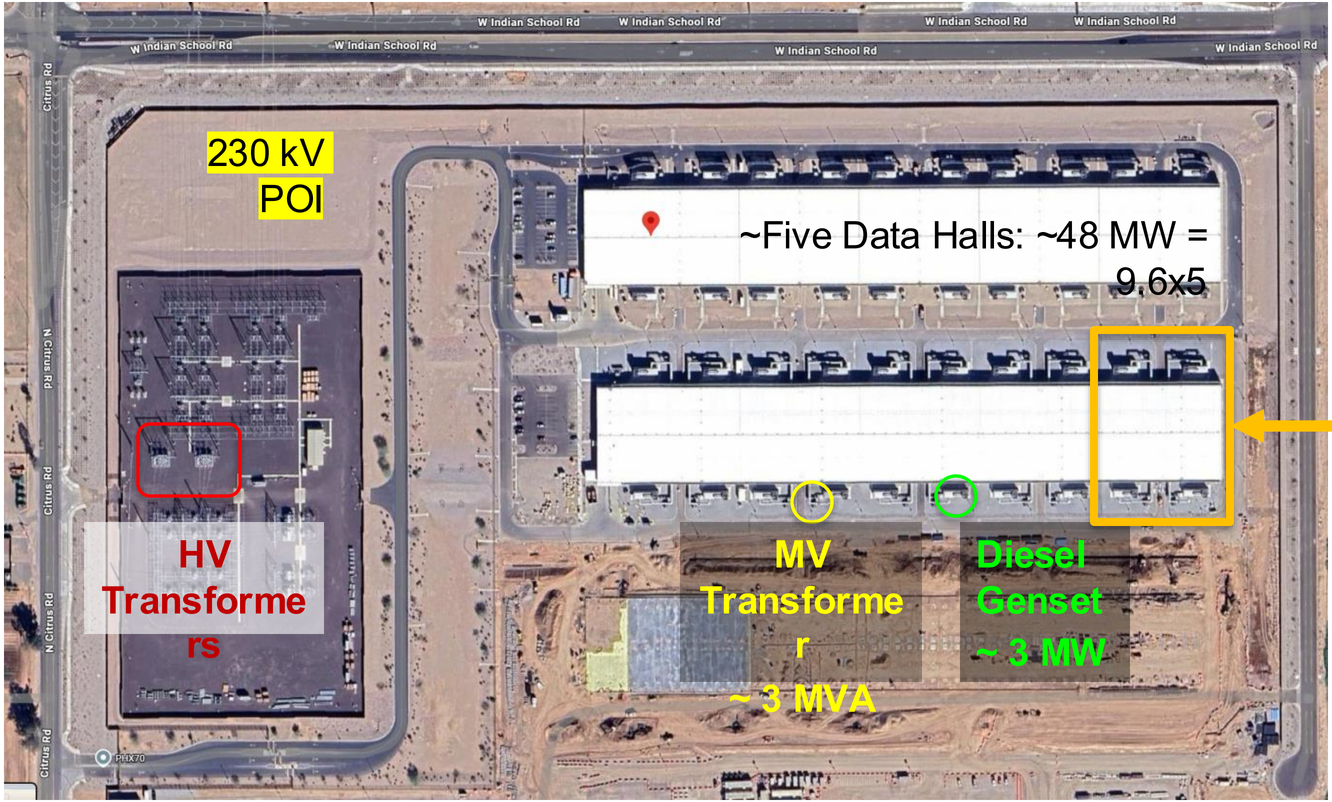
Outline

- Factor to Consider for EMT Modeling of Data Centers
  - Data Center Power System Architecture
  - Power Converters in Data Centers that Interface with Grid
  - Operation Modes of AC UPS
- Types of Converter Driven Control Interactions in Data Centers
- EMT PSCAD Model of an IT Rack
  - PSU Based on Single-Phase Totem-Pole Bridgeless PFC Topology
  - Averaging Techniques for Fast EMT Simulation of Data Centers
  - Impedance-Based Stability Analysis

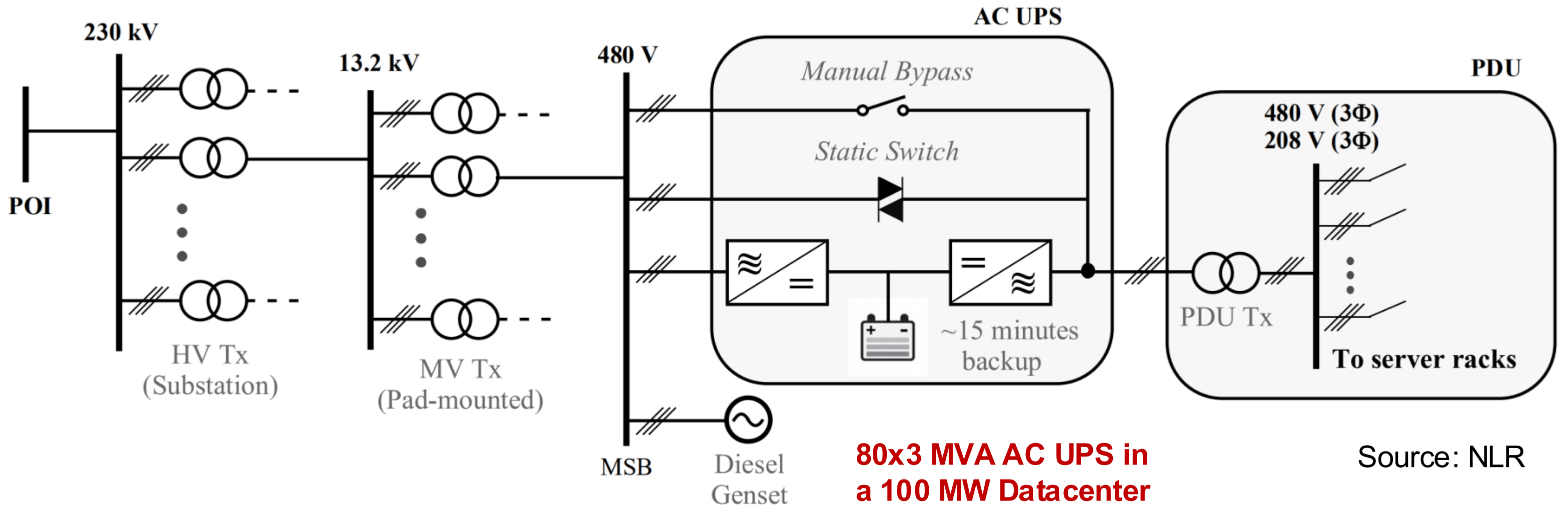
Data Center Near Phoenix, AZ (~100 MW)



- 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 (N+1 redundancy), and numerous IT server racks

Image Source: Google Maps

Data Center Architecture: From POI to IT Racks



80x3 MVA AC UPS in a 100 MW Datacenter

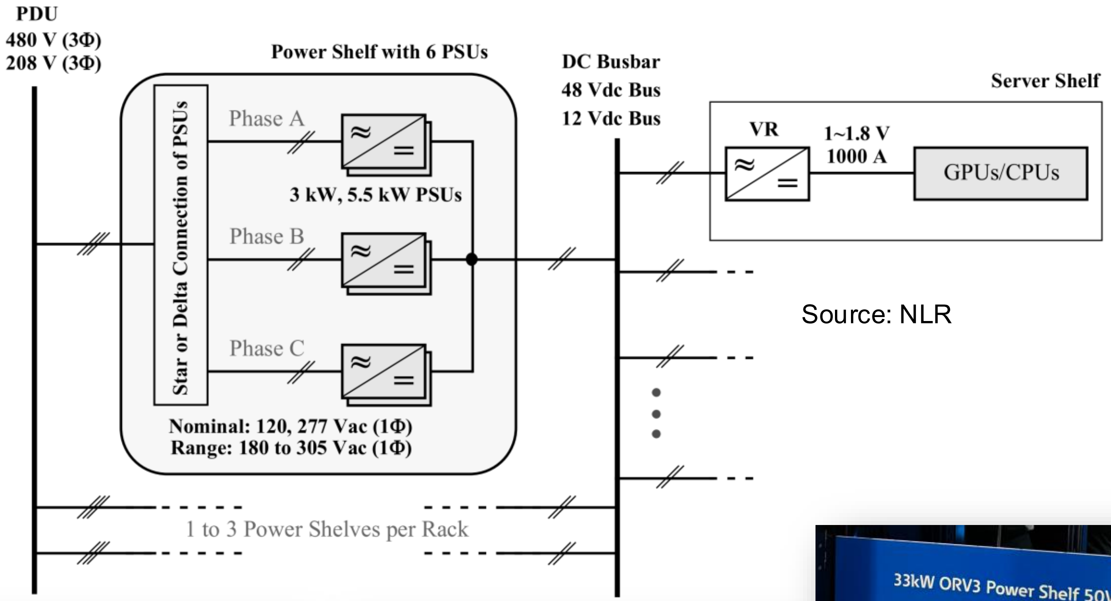
Source: NLR

40x3 MVA Genset in a 100 MW Datacenter

- HV Tx: High-voltage Transformer
- MV Tx: Medium-voltage Transformer
- MSB: Main Switch Board

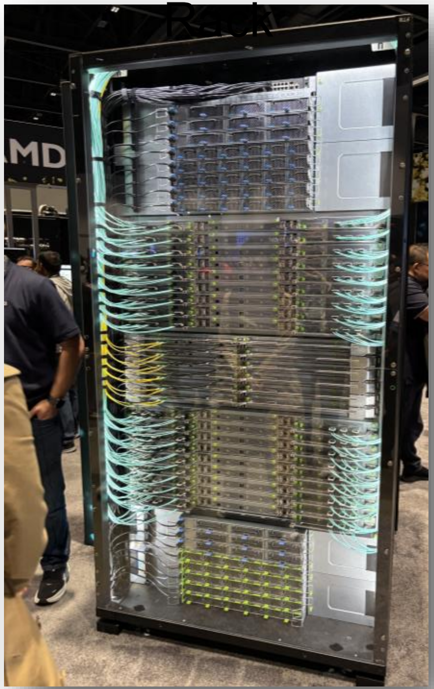
- UPS: Uninterruptible Power Supply
- PDU: Power distribution Unit
- PDU Tx is not always required

Data Center Architecture: Inside IT Racks



Source: NLR

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 (NLR)

Factors to Consider for EMT Modeling of Data Centers

Architecture of Data Center Power System

Power Delivery (from POI to IT Racks)

- AC UPS
- DC UPS
- SST
- Side Car

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
- Small-Signal Stability
  - Low Frequency
  - High Frequency

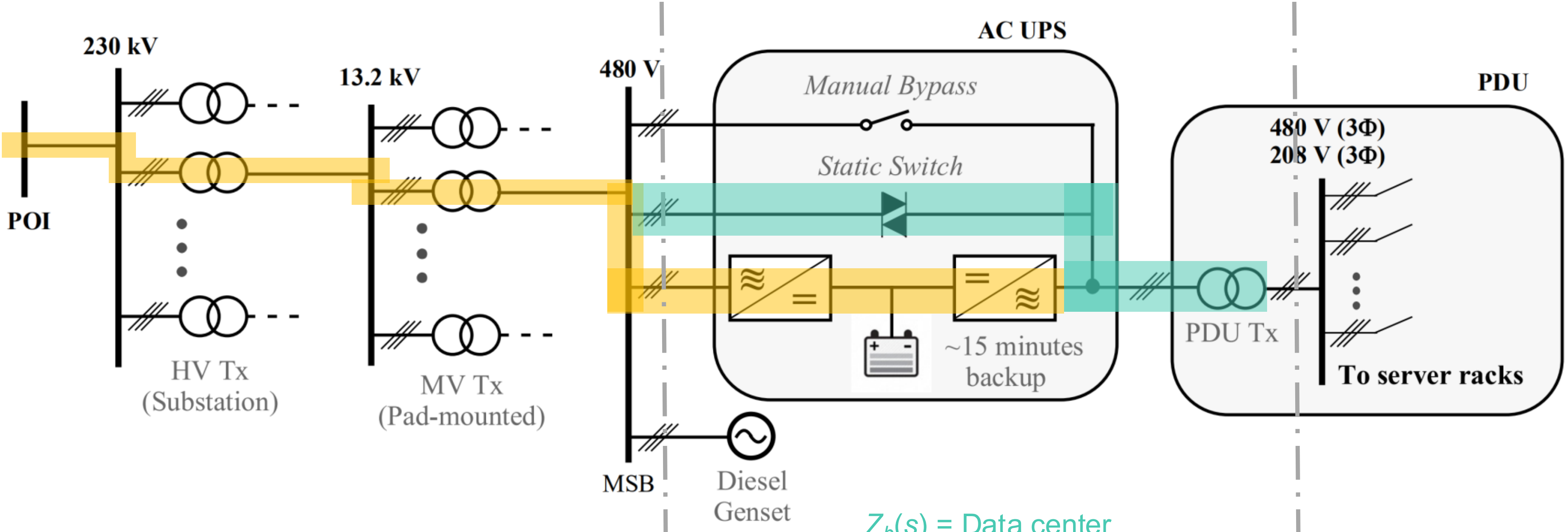
UPS: *Uninterruptible Power Supply*
PSU: *Power Supply Unit*
BBU: *Battery Backup Unit*
CBU: *Capacitor Bank Unit*
SST: *Solid-State Transformer*

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

Summary

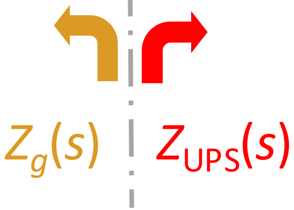
- Generally, two types of power electronic converters in the data center power systems can interface with the grid:
  - AC UPS
  - PSU
- Tens to hundreds of AC UPS, each rated at few megawatts, are present in a large data center
  - Power electronic converters inside AC UPS can interact with the grid when the AC UPS is operated in so-called **double conversion mode**
- Tens to hundreds of thousands of PSUs, each rated at few kilowatts, are present in a large data center
  - Power electronic converters inside PSU can interact with the grid when the AC UPS is operated in so-called **bypass or eco mode**

Two Types of Converter-Driven Control Interactions



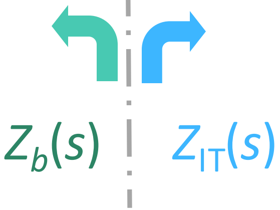
$Z_g(s)$ = Grid Impedance at the terminal of the UPS

$Z_{UPS}(s)$ = Impedance Response of the UPS

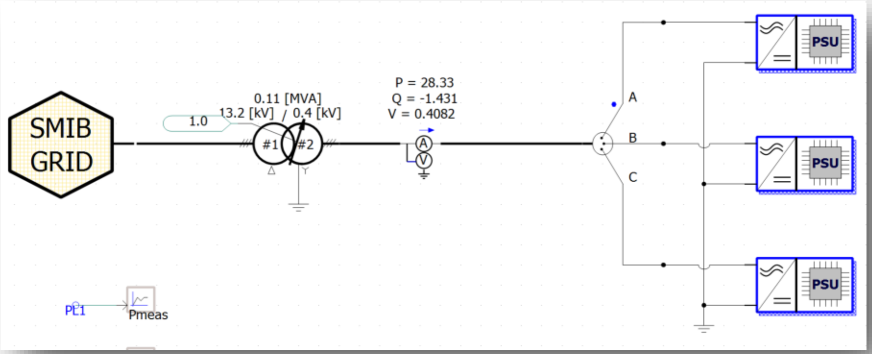


$Z_b(s)$ = Data center Building Impedance Response

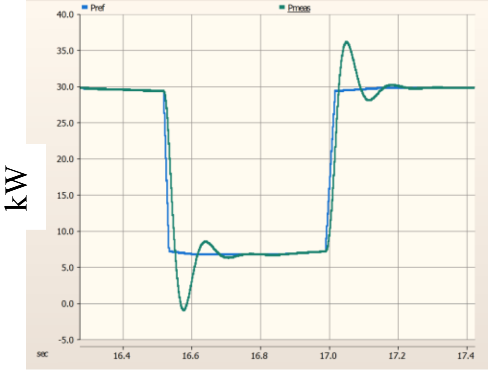
$Z_{IT}(s)$ = IT Rack Impedance Response



PSCAD Model of a 33 kW IT Rack (3 x 2 x 5.5 kW PSUs)

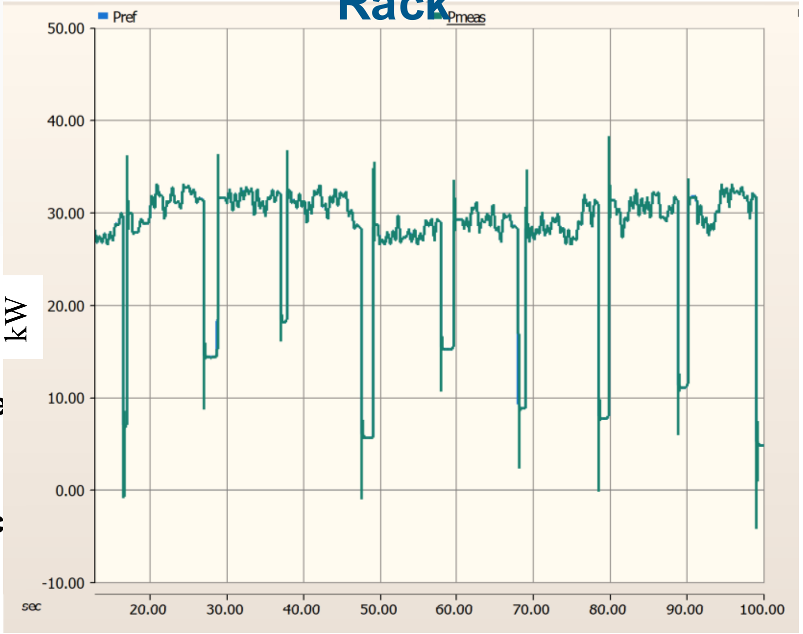


AC vs DC Power

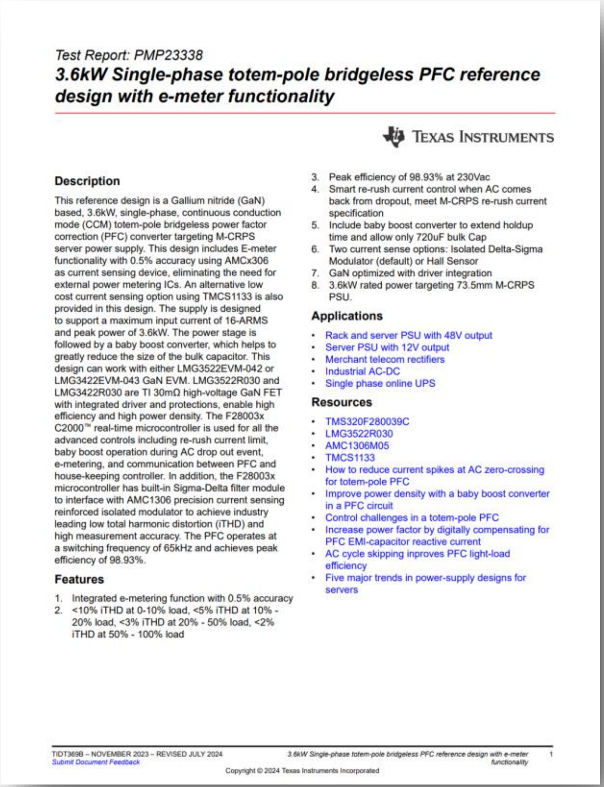


- P_{ref}: DC Power (GPU Power Consumption)
  - Ramp rate = 43 pu/sec
- P_{meas}: AC Power by IT Rack (Experienced by UPS)
  - Ramp Rate = 22 pu/sec
  - Overshoot: 0.25 p.u.

Power Consumption by the IT Rack



TI Refence Design Used for EMT Modeling of a PSU



Test Report: PMP23338

3.6kW Single-phase totem-pole bridgeless PFC reference design with e-meter functionality

TEXAS INSTRUMENTS

Description

This reference design is a Gallium nitride (GaN) based, 3.6kW, single-phase, continuous conduction mode (CCM) totem-pole bridgeless power factor correction (PFC) converter targeting M-CRPS server power supply. This design includes E-meter functionality with 0.5% accuracy using AMCx306 as current sensing device, eliminating the need for external power metering ICs. An alternative low cost current sensing option using TMCS1133 is also provided in this design. The supply is designed to support a maximum input current of 16-ARMS and peak power of 3.6kW. The power stage is followed by a baby boost converter, which helps to greatly reduce the size of the bulk capacitor. This design can work with either LMG3522EVM-042 or LMG3422EVM-043 GaN EVM. LMG3522R030 and LMG3422R030 are TI 30mΩ high-voltage GaN FET with integrated driver and protections, enable high efficiency and high power density. The F28003x C2000™ real-time microcontroller is used for all the advanced controls including re-rush current limit, baby boost operation during AC drop out event, e-metering, and communication between PFC and house-keeping controller. In addition, the F28003x microcontroller has built-in Sigma-Delta filter module to interface with AMC1306 precision current sensing reinforced isolated modulator to achieve industry leading low total harmonic distortion (iTHD) and high measurement accuracy. The PFC operates at a switching frequency of 65kHz and achieves peak efficiency of 98.93%.

Features

1. Integrated e-metering function with 0.5% accuracy
2. <10% iTHD at 0-10% load, <5% iTHD at 10% - 20% load, <3% iTHD at 20% - 50% load, <2% iTHD at 50% - 100% load
3. Peak efficiency of 98.93% at 230Vac
4. Smart re-rush current control when AC comes back from dropout, meet M-CRPS re-rush current specification
5. Include baby boost converter to extend holdup time and allow only 720uF bulk Cap
6. Two current sense options: Isolated Delta-Sigma Modulator (default) or Hall Sensor
7. GaN optimized with driver integration
8. 3.6kW rated power targeting 73.5mm M-CRPS PSU.

Applications

- Rack and server PSU with 48V output
- Server PSU with 12V output
- Merchant telecom rectifiers
- Industrial AC-DC
- Single phase online UPS

Resources

- TMS320F280039C
- LMG3522R030
- AMC1306M05
- TMCS1133
- How to reduce current spikes at AC zero-crossing for totem-pole PFC
- Improve power density with a baby boost converter in a PFC circuit
- Control challenges in a totem-pole PFC
- Increase power factor by digitally compensating for PFC EMI-capacitor reactive current
- AC cycle skipping inproves PFC light-load efficiency
- Five major trends in power-supply designs for servers

TIDT369B – NOVEMBER 2023 – REVISED JULY 2024
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3.6kW Single-phase totem-pole bridgeless PFC reference design with e-meter functionality 1
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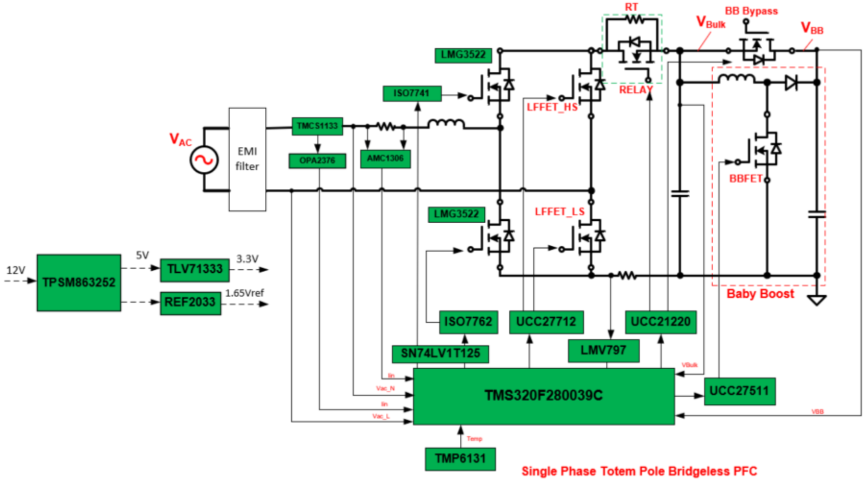
- Architecture of TI PMP23338 Ref. Design

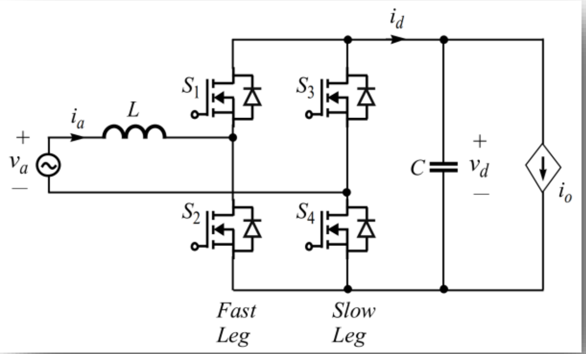


Source: Texas Instruments (TI)

- **TI has supported the NLR team on the development of the EMT model by providing information on PSU control system design and typical parameters used in the reference design.**

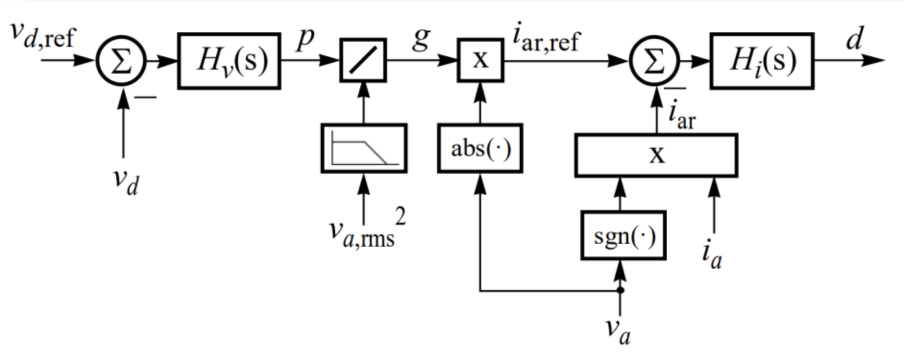
Single-Phase Bridgeless Totem-pole PFC (TPPFC)

- **Topology**



- Fast leg switching frequency is 50 kHz to 150 kHz
  - **Simulation timestep should be smaller than 1 µs to capture the switching dynamics**
    - Not important for power system studies
- Slow leg switching frequency is the same as the fundamental frequency, 60 Hz

- **Control Design**

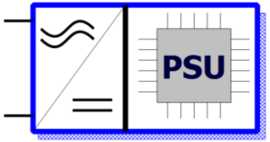


- Current control bandwidth is 5 kHz to 15 kHz
  - **Simulation timestep should be smaller than 10 µs to capture the current control dynamics**
    - Usually not important for power system studies

PSCAD Model of a Single-Phase TPPFC-Based PSU

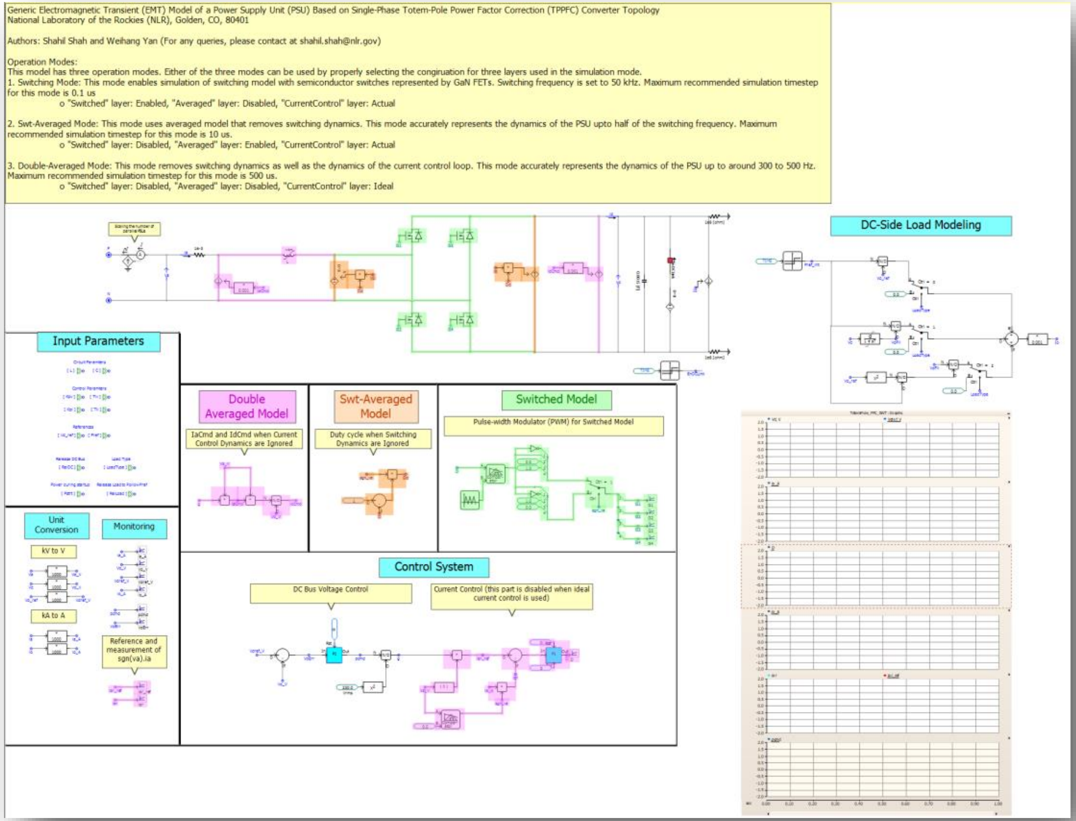
- **PSCAD Library Component**

Input 1ϕ Voltage: **LVAC**



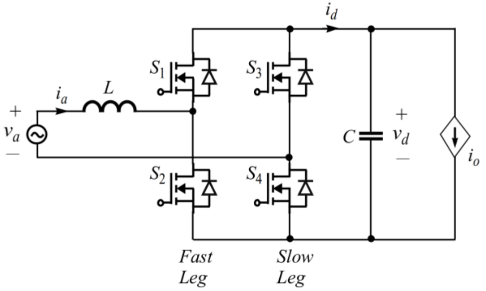
Output Voltage: **400 Vdc**

- **Features of the Model**
  - Can represent PSUs of different ratings
  - Advanced averaging techniques to enable fast EMT simulations
    - Three modes of operation for the model
  - GPU load can be represented as constant resistance, constant current, or constant power load
  - GPU load profile can be supplied directly to the EMT model



Averaging Techniques

- Switching Averaged Model
  - Ts < 10 μs

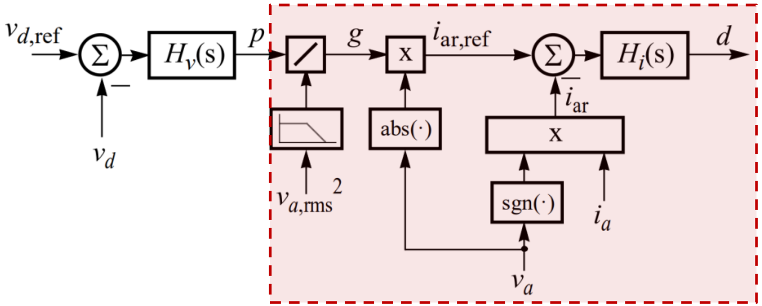


$$\text{for } v_a \geq 0: \begin{cases} L\frac{di_a}{dt} = v_a - (1-d)v_d \\ i_d = (1-d)i_a \end{cases}$$

$$\text{for } v_a < 0: \begin{cases} L\frac{di_a}{dt} = v_a + (1-d)v_d \\ i_d = -(1-d)i_a \end{cases}$$

  - Captures dynamics up to 10kHz

- Double Averaged Model
  - Ts < 100 μs



$$i_{ar} = i_{ar,\text{ref}} \Rightarrow i_a = p \cdot \frac{v_a}{V_{\text{rms}}^2} \text{ and } i_d = p \cdot \frac{v_a^2}{V_{\text{rms}}^2} \cdot \frac{1}{v_d}$$

  - Captures dynamics up to 1 kHz

Comparison of 5.5 kW TPPFC Models

v_d

i_a

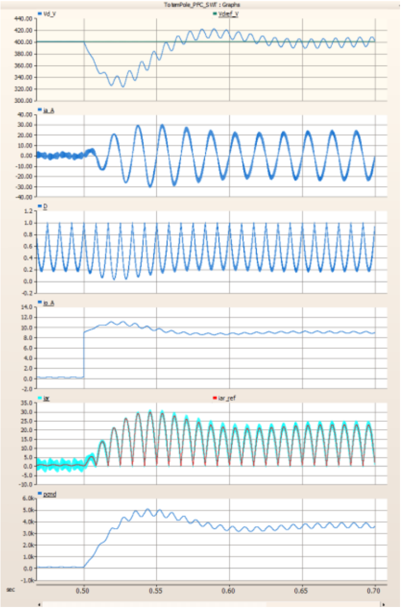
d

i_o

i_{ar}

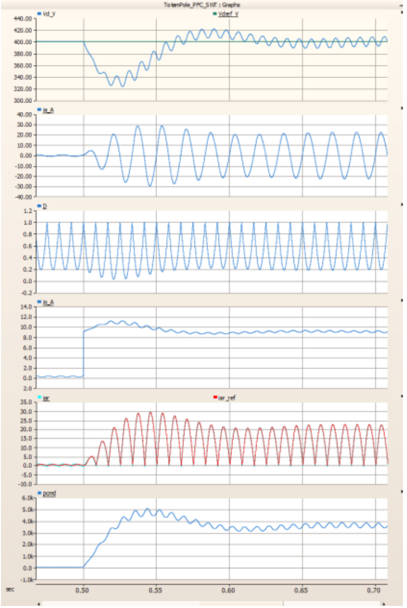
p

Switched Model



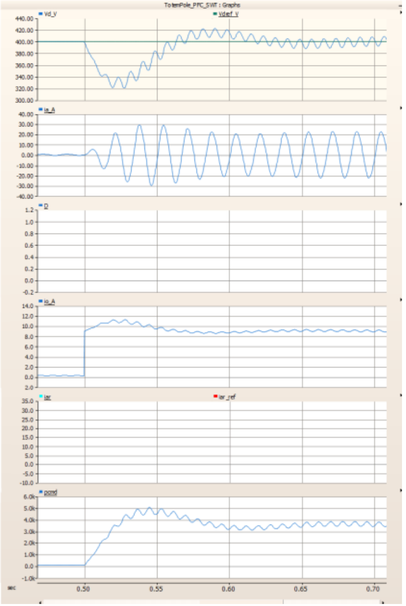
- Simulation time step: 0.1 μs
- Time for simulating one sec.: 53 s

Swt-Averaged Model



- Simulation time step: 10 μs
- Time for simulating one sec.: 0.86 s

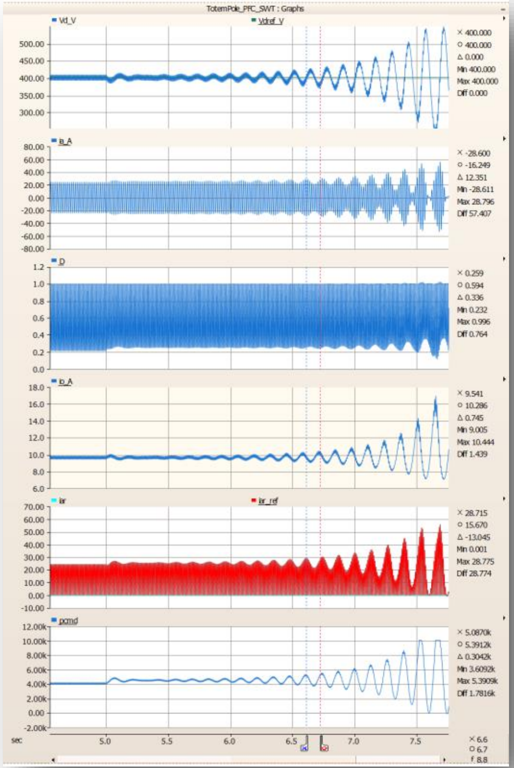
Double-Averaged Model

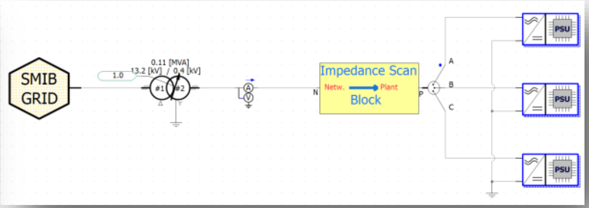


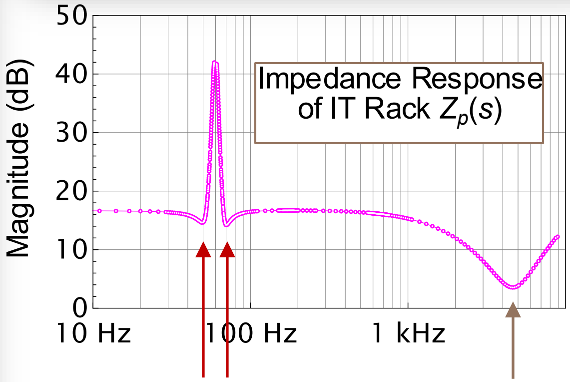
- Simulation time step: 500 μs
- Time for simulating one sec. : 0.12 s

Weak Grid Instability in Datacenters

- UPS Bypass Mode
  - Instability observed at 9 Hz under weak grid conditions
    - The frequency of instability is strongly correlated with dc voltage control design in PSUs used within IT Racks
- Double Conversion Mode
  - Weak grid instability mechanism is the same as in IBRs







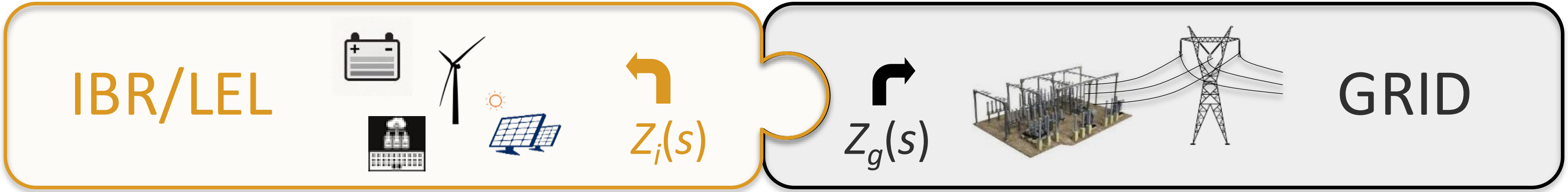
Dips from dc voltage control

BW: 10 Hz

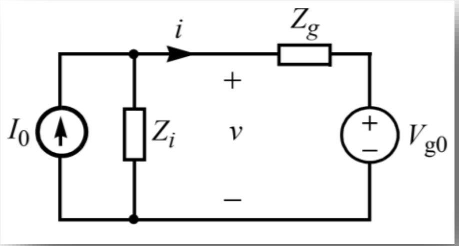
Dips from current control

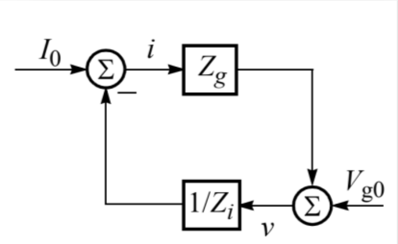
BW: 5 kHz

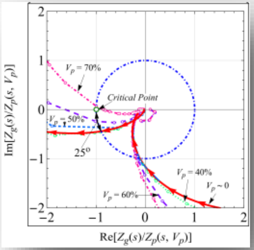
Impedance-Based Stability Analysis

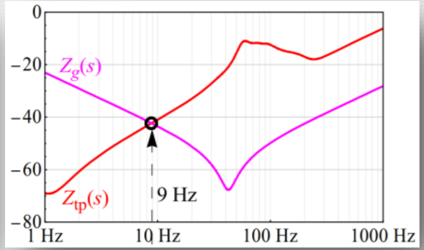


- **Loop Gain**: $Z_g(s)/Z_i(s)$
- **Pre-requisite:**
  - *Standard Criterion*: IBR and the Grid are Separately Stable
  - *Reversed Criterion*: IBR and the Grid are Stable when Interconnected





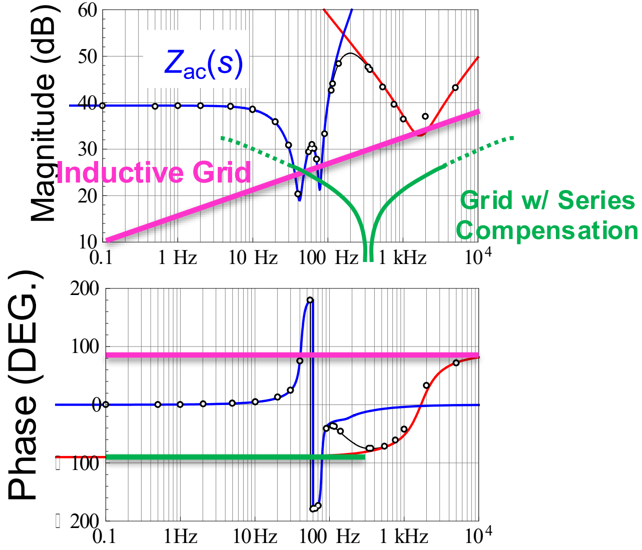




Mechanism of Control Interactions in Data Centers

- Impedance of Single-Phase VSC

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



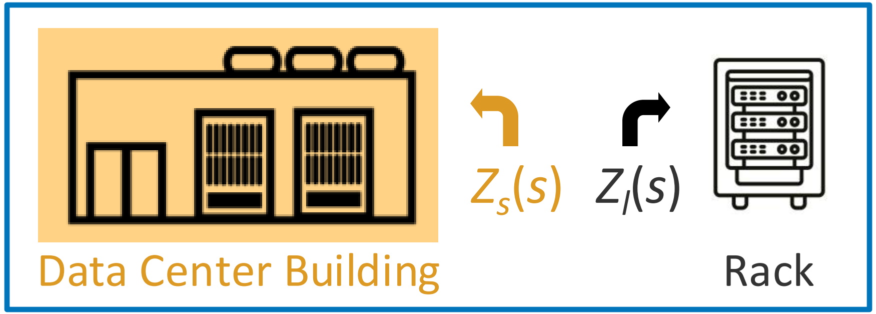
- Impedance response of single-phase VSCs (such as PSUs) has two dips around the fundamental frequency and it exhibits negative damping
  - These dips can interact adversely with inductive or capacitive impedance of the source (grid + distribution network) and potentially create low-frequency oscillations
  - The distance of the dips from the fundamental frequency is correlated with the bandwidth of dc-bus voltage control in the single-phase PFC front-end of the PSU.

Ref.: Shahil Shah, "On impedance modeling of single-phase voltage source converters," IEEE ECCE, 2016.

Impedance-Based Specifications from Meta

- Building 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

Summary

- AC UPS are the power electronic converters seen by the grid withing a data center when they operate in the double conversion mode
  - Modeling of AC UPS is very similar to IBRs, if not the same, as they use similar inverters (PCS). Hence, existing knowhow on EMT modeling of IBRs can be directly leveraged.

- PSUs are the power electronic converters seen by the grid within a data center power system during normal operation when AC UPS is operated in the bypass mode.
  - Single-phase PFC ac-dc converters are the front-end within a PSU and they must be accurately modeled for evaluating control interactions between datacenters and power grids.
  - The switching frequency of PSUs range from 10s to 100s of kHz. The current control bandwidths range from few to 10s of kHz. These high frequency dynamics do not penetrate the grid; hence, switching frequency and current control dynamics can be ignored in the PSU models used for grid reliability studies.

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shahil.shah@nlr.gov

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