Battery Energy Storage System Modeling

A Digital Twin based Approach

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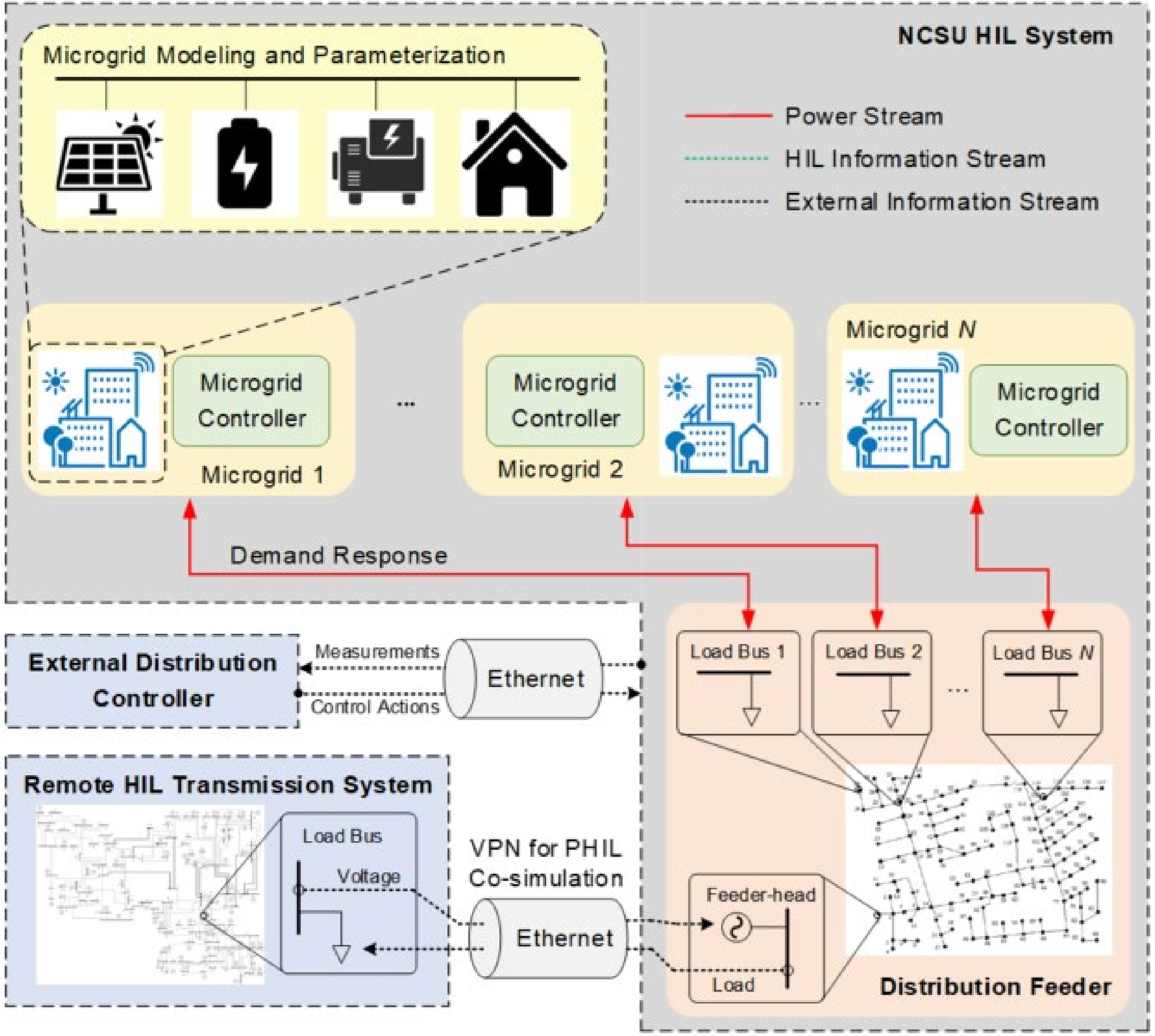
Outline

- What is a Digital Twin based Approach?
  - Simulation Platforms
  - Battery Models
  - Battery Device-level Controllers
  - Energy Management Systems
- Modeling Considerations
- Conclusions



https://sites.google.com/a/ncsu.edu/ninglu/pars-platform?authuser=0

A Digital-twin based Approach

Model Architecture

Digital Twin Based Approach

Reference	Modeling Considerations	Synchronization	Communication
[1]	Electromagnetic transients + phasor model	Yes	N/A
[2]	Electromagnetic transients + phasor model	Yes	N/A
[3]	Phasor model	Yes	Wireless communication simulator
[4]	Electromagnetic transients + hardware	Asynchronous	N/A
[5]	Phasor model + hardware	Asynchronous	JSON-link over Ethernet
Digital Twin based Approach [6-10]	Electromagnetic transients + phasor model + hardware **+ Parameter Updates** **+ Communication Links** **+ Energy/Power Management Systems**	Asynchronous	Modbus and file-shared over Ethernet

1. Plumier, Frédéric, et al. "Co-simulation of electromagnetic transients and phasor models: A relaxation approach." *IEEE Transactions on Power Delivery* 31.5 (2016): 2360-2369.
2. Palmintier, Bryan, et al. "Design of the HELICS highperformance transmission-distribution-communication-market co-simulation framework." Proc. 2017 Workshop on Modeling and Simulation of Cyber-Physical Energy Systems, Pittsburgh, PA. 2017.
3. Godfrey, Tim, et al. "Modeling smart grid applications with cosimulation." Smart Grid Communications (SmartGridComm), 2010 First IEEE International Conference on. IEEE, 2010.
4. Godfrey, Tim, et al. "Modeling smart grid applications with cosimulation." Smart Grid Communications (SmartGridComm), 2010 First IEEE International Conference on. IEEE, 2010.
5. Palmintier, Bryan, et al. "A power hardware-in-the-loop platform with remote distribution circuit cosimulation." IEEE Transactions on Industrial Electronics 62.4 (2015): 2236-2245.
6. F. Xie, H. Yu, Q. Long, W. Zeng and N. Lu, "Battery Model Parameterization Using Manufacturer Datasheet and Field Measurement for Real-Time HIL Applications," in IEEE Transactions on Smart Grid, vol. 11, no. 3, pp. 2396-2406, May 2020, doi: 10.1109/TSG.2019.2953718.
7. F. Xie, C. McEntee, M. Zhang, B. Mather and N. Lu, "Development of an Encoding Method on a Co-Simulation Platform for Mitigating the Impact of Unreliable Communication," in IEEE Transactions on Smart Grid, vol. 12, no. 3, pp. 2496-2507, May 2021, doi: 10.1109/TSG.2020.3039949. Videos related with the paper: https://www.youtube.com/watch?v=SdibDKEpw60.
8. F. Xie et al., "Networked HIL Simulation System for Modeling Large-scale Power Systems," 2020 52nd North American Power Symposium (NAPS), 2021, pp. 1-6, doi: 10.1109/NAPS50074.2021.9449646.
9. Bei Xu, Victor Paduani, David Lubkeman, and Ning Lu, "A Novel Grid-forming Voltage Control Strategy for Supplying Unbalanced Microgrid Loads Using Inverter-based Resources," 22PESGM1399, submitted to 2022 PES General meeting. Available online at: https://arxiv.org/pdf/2111.09464.pdf
10. Victor Paduani, Bei Xu, David Lubkeman, Ning Lu, "Novel Real-Time EMT-TS Modeling Architecture for Feeder Blackstart Simulations," 22PESGM1449, submitted to 2022 IEEE PESGM. Available online at: https://arxiv.org/pdf/2111.10031.pdf

Photovoltaic Analysis and Response Support (PARS) platform

https://sites.google.com/a/ncsu.edu/ninglu/pars-platform?authuser=0

Highly Scalable

High Fidelity

Grid-forming:

μs-level EMT domain

Grid-following:

Ms-level phasor domain

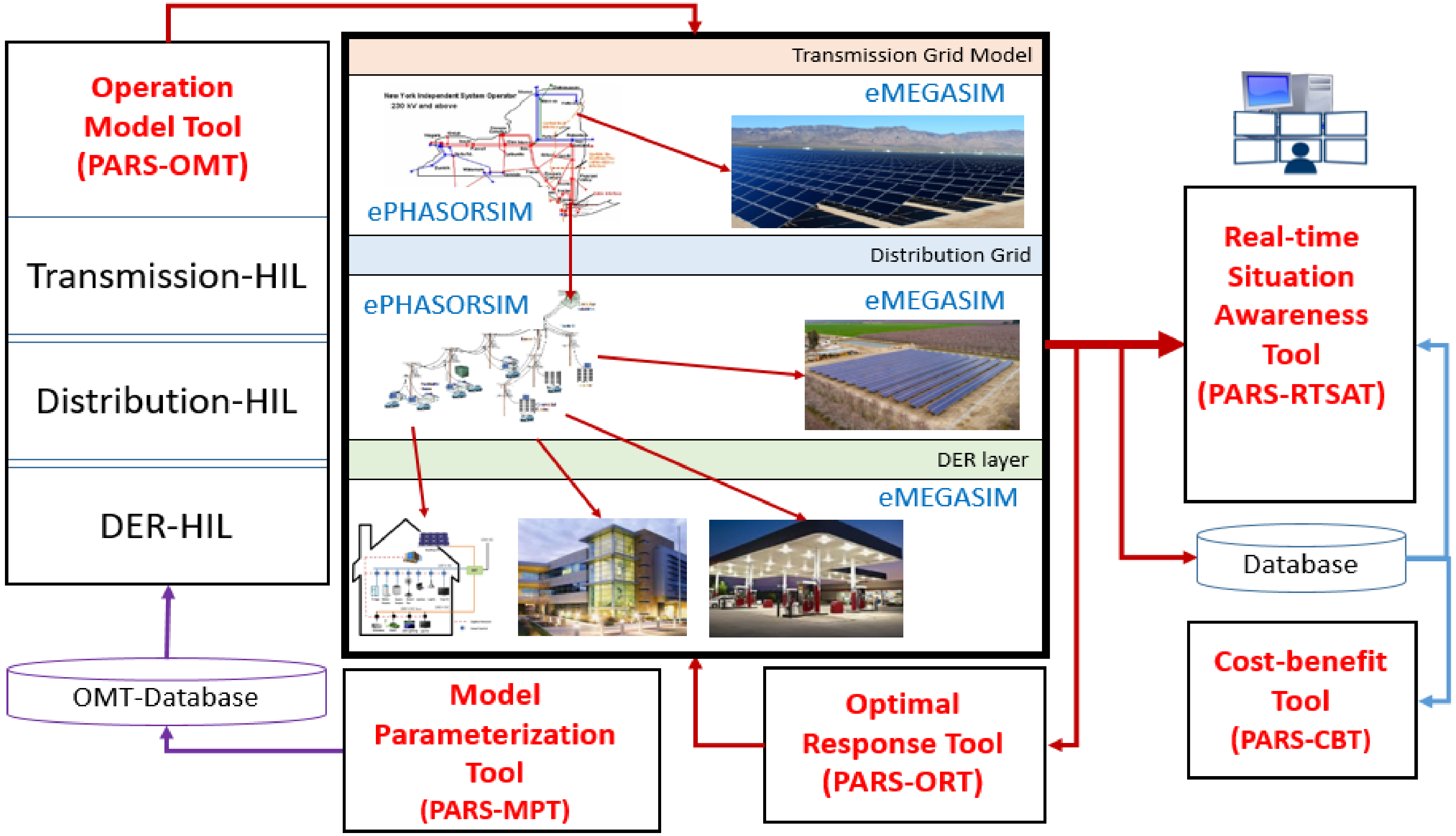
Power Management:

Intra 5-min quasi-steady-state

Energy Management:

5-Minute to 24-ahead

An OPAL-RT based Real-time PARS Platform



Operation Model Tool (PARS-OMT)
Transmission-HIL
Distribution-HIL
DER-HIL
OMT-Database
Transmission Grid Model
eMEGASIM
ePHASORSIM
Distribution Grid
ePHASORSIM
eMEGASIM
DER layer
eMEGASIM
Real-time Situation Awareness Tool (PARS-RTSAT)
Database
Cost-benefit Tool (PARS-CBT)
Model Parameterization Tool (PARS-MPT)
Optimal Response Tool (PARS-ORT)

Realistic

Realistic network models

Realistic PV and load profiles

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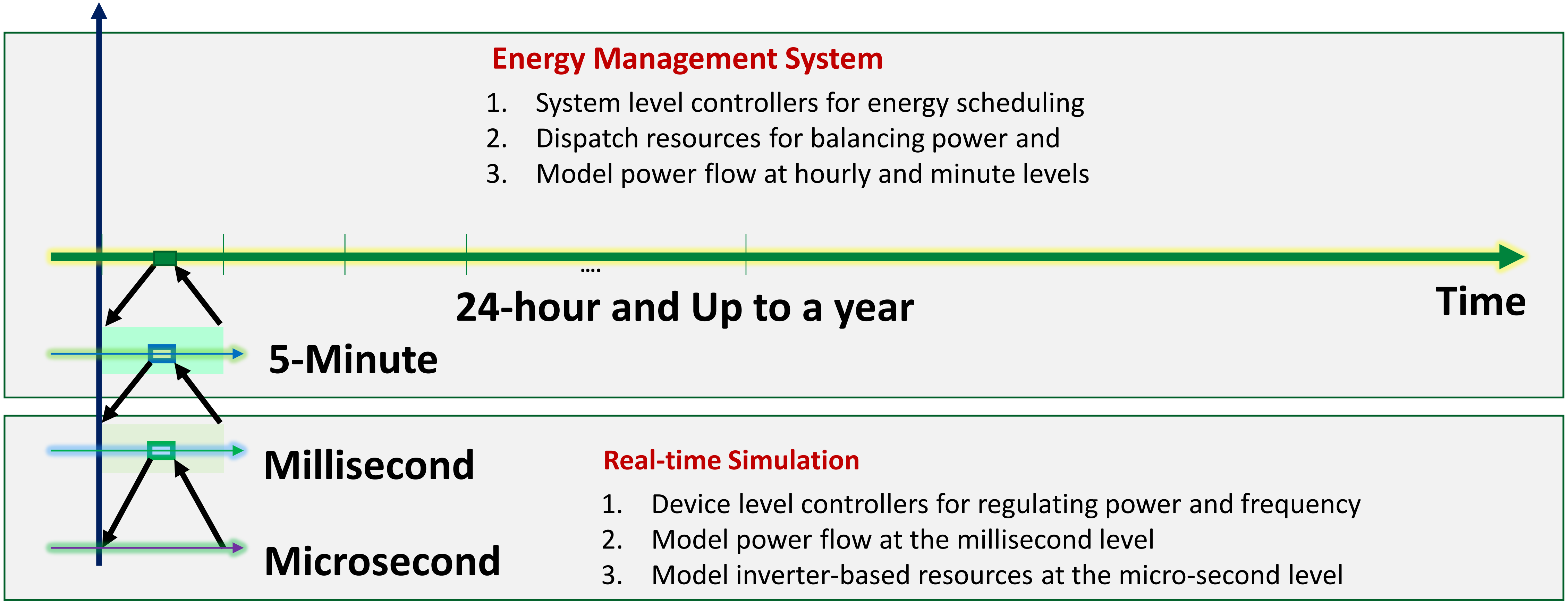
Simulation Time-line



Energy Management System

1. System level controllers for energy scheduling
2. Dispatch resources for balancing power and
3. Model power flow at hourly and minute levels

Real-time Simulation

1. Device level controllers for regulating power and frequency
2. Model power flow at the millisecond level
3. Model inverter-based resources at the micro-second level

Uniqueness of the PARS platform

- **Sequence of grid operation:** Energy management, power balance, frequency and voltage regulation
- **Device-level and system-level controller interactions** via realistic communication protocols
- **Model both Fast and slow transients**
- **Impacts of communication delays**, errors, cyber attacks on controlling distributed energy resources.

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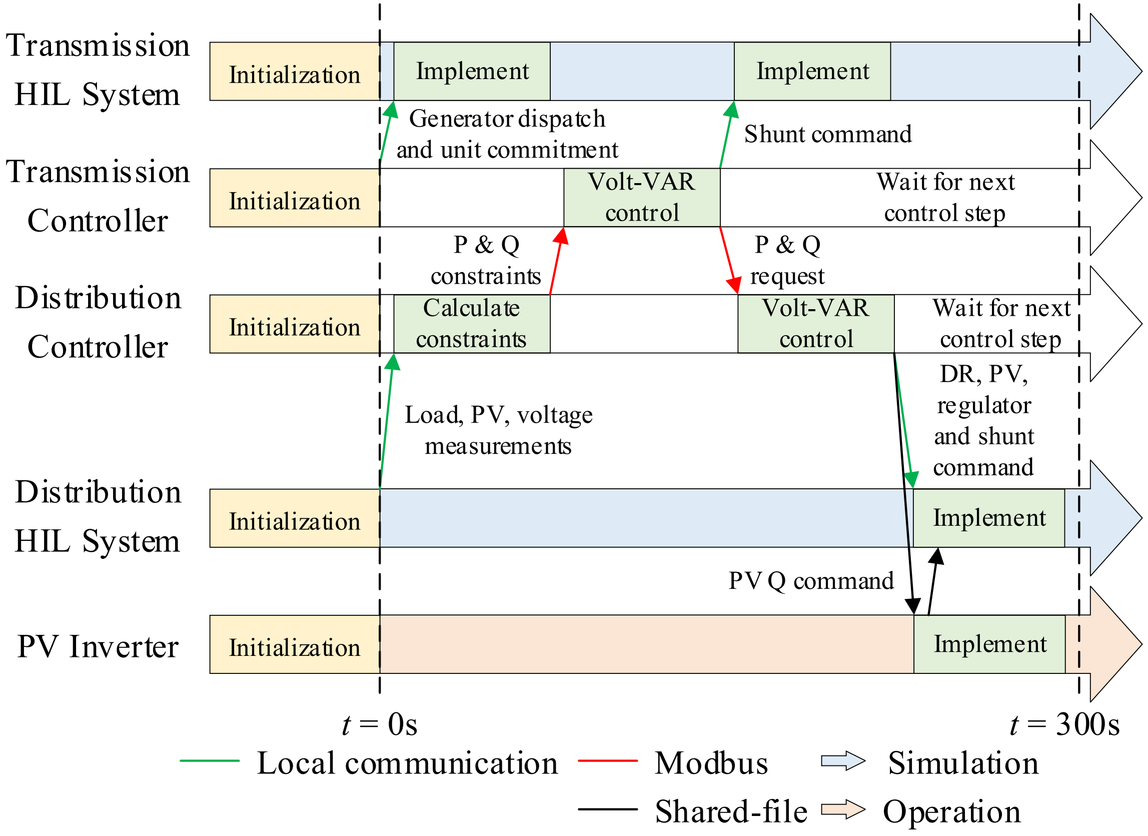
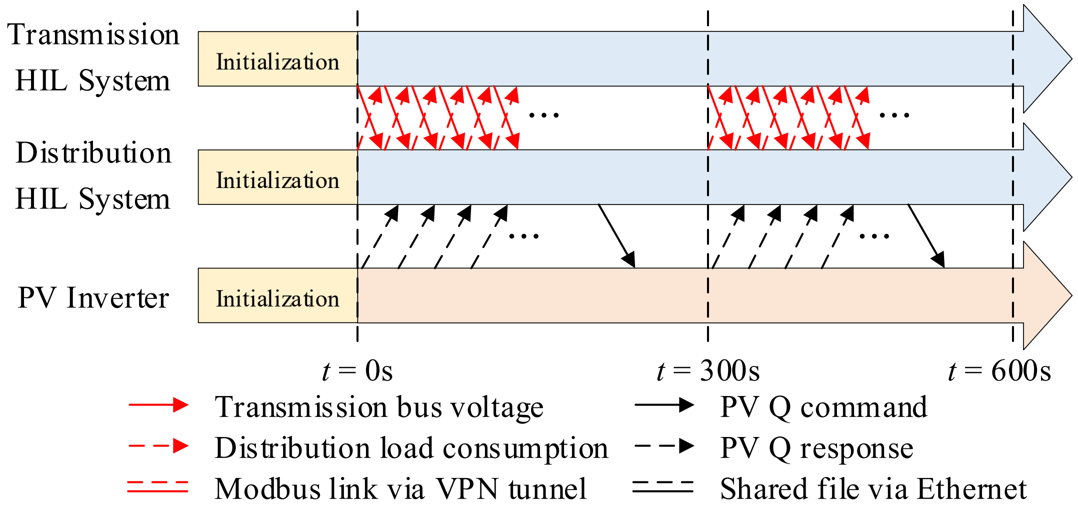
System Modeling Timeline

HIL Simulators – External Controller Coordination



HIL Simulators Coordination



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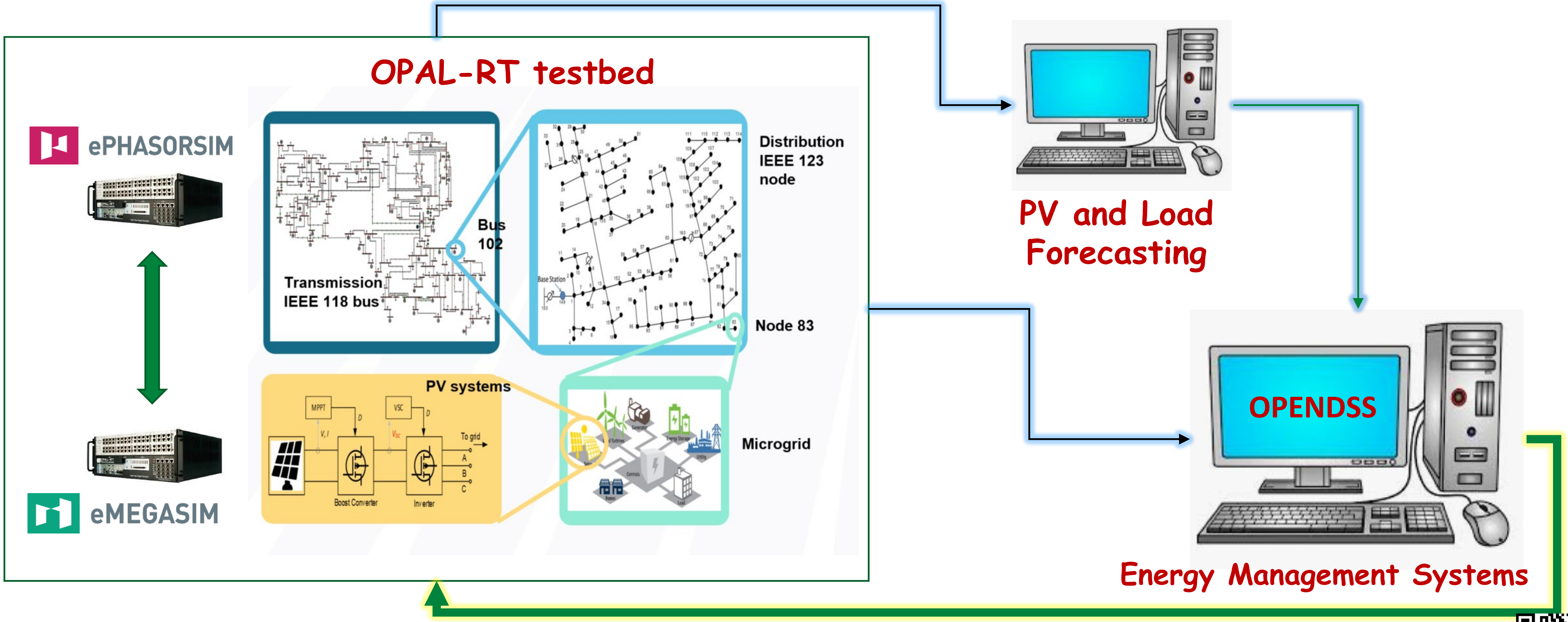
Asynchronous Modeling Framework



OPENDSS for **faster-than-real-time** simulation (Quasi-steady state)
OPAL-RT for **real-time** simulation (EMT and phasor-based)

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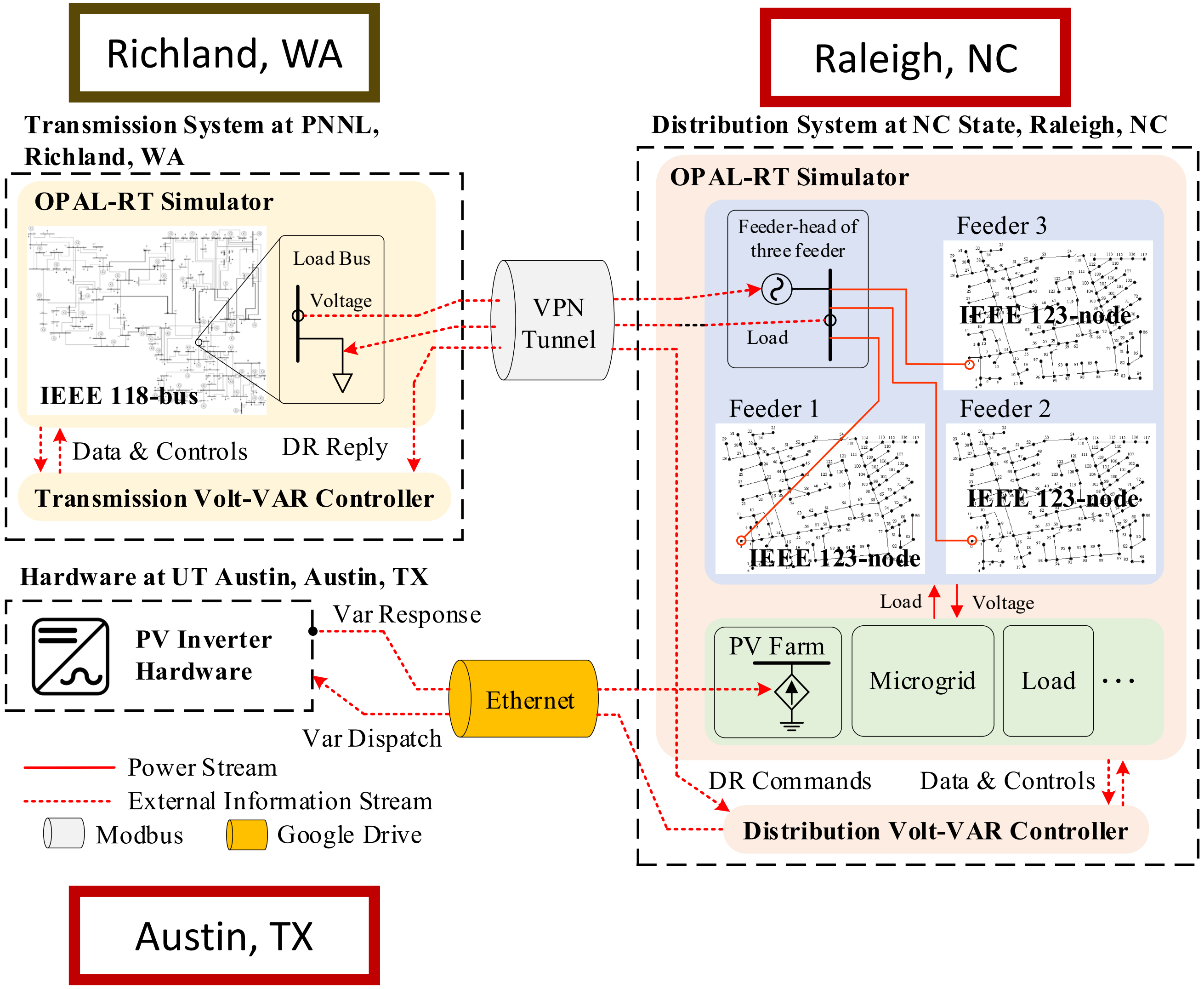
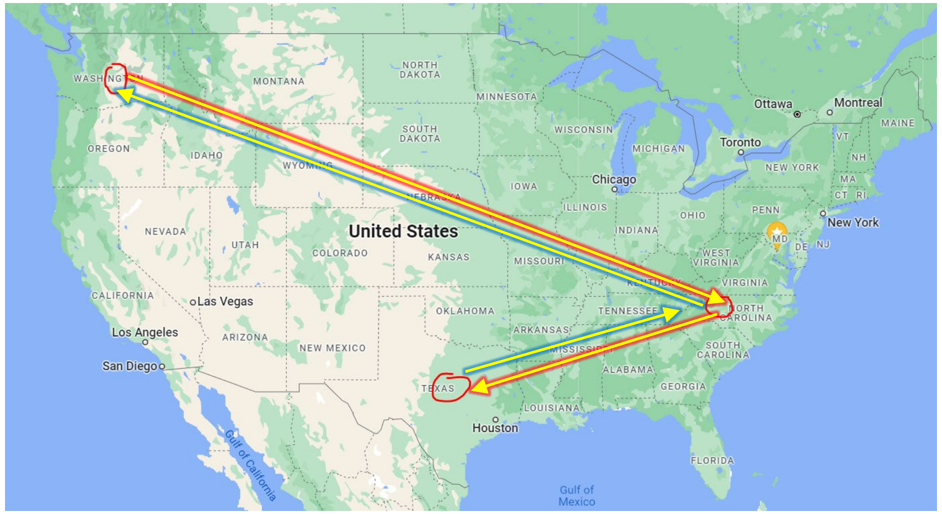
A Network of Digital Twins





1. F. Xie, C. McEntee, M. Zhang, B. Mather and N. Lu, "Development of an Encoding Method on a **Co-Simulation Platform for Mitigating the Impact of Unreliable Communication**," in IEEE Transactions on Smart Grid, vol. 12, no. 3, pp. 2496-2507, May 2021, doi: 10.1109/TSG.2020.3039949.
2. F. Xie et al., "**Networked HIL Simulation System** for Modeling Large-scale Power Systems," 2020 52nd North American Power Symposium (NAPS), 2021, pp. 1-6, doi: 10.1109/NAPS50074.2021.9449646.
3. Ke, Xinda, Nader Samaan, Jesse Holzer, Renke Huang, Bharat Vyakaranam, Mallikarjuna Vallem, Marcelo Elizondo et al. "**Coordinative real-time sub-transmission** volt–var control for reactive power regulation **between transmission and distribution systems**." *IET Generation, Transmission & Distribution* (2018).

Battery System Model

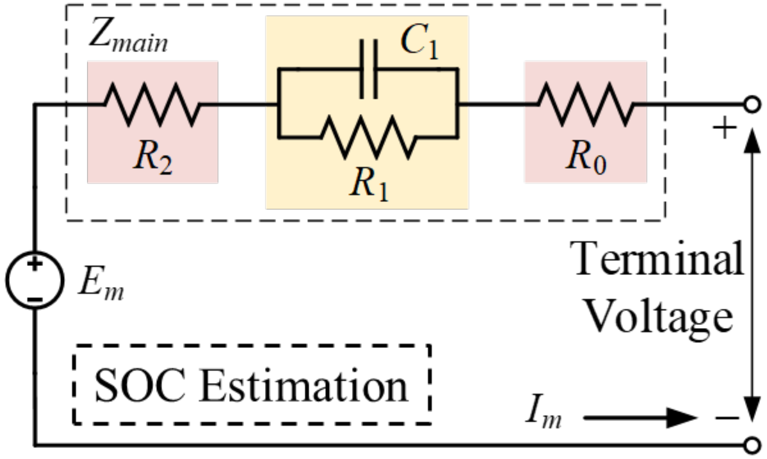
Reference Paper: F. Xie, H. Yu, Q. Long, W. Zeng and N. Lu, "Battery Model Parameterization Using Manufacturer Datasheet and Field Measurement for Real-Time HIL Applications," in *IEEE Transactions on Smart Grid*, vol. 11, no. 3, pp. 2396-2406, May 2020, doi: 10.1109/TSG.2019.2953718.

Battery Models

Battery Models

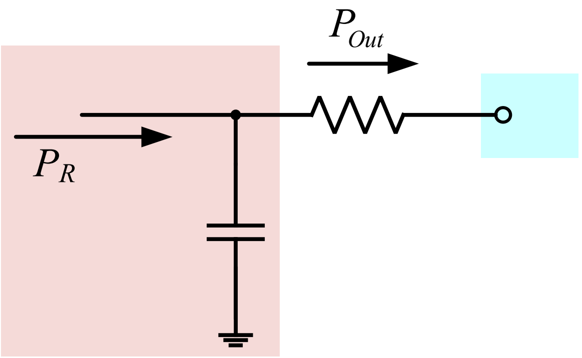
Electrical main branch circuit

Variable	Description
E_m	Internal voltage source
R_0	Terminal resistance
R_1	Dynamics branch resistance
C_1	Dynamics branch capacitance
R_2	Thermodynamic resistance
Z_{main}	Branch equivalent impedance



Thermodynamic branch circuit

Variable	Description
R_T	Thermal resistance
C_T	Battery thermal capacitance
P_R	Internal heat loss from R_2 and R_0
P_{Out}	Heat exchange
T	Battery internal temperature
T_a	Ambient temperature



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Objective Functions of Parameterization

Goal: Find an optimal set of model parameters

Approach: Minimize the mismatch between simulation results and field measurements is minimized.

$$\min_{\theta\in\mathbb{R}^N}\left\{F(\theta)=\sum_{r=1}^{3}\boxed{w_r}\cdot\boxed{f_r(\theta)}:\boxed{l\le\theta\le u,}\ l,u\in\mathbb{R}^N\right\}$$

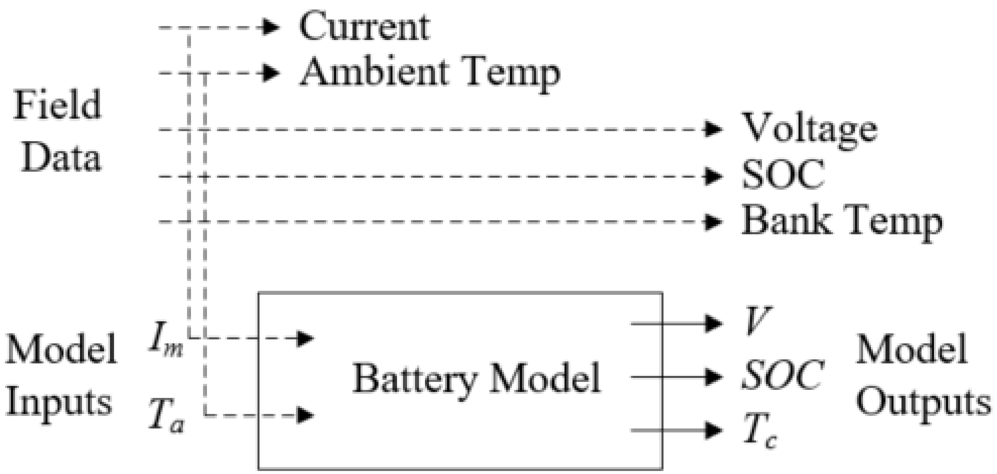
$$\sum_{r=1}^{3}w_r=1$$

The weighting factor for different measurements.

Constraints on model parameters.

$$f(\theta)=\sum_{t=1}^{N_{sample}}\left(x(\theta,t)-\tilde{x}(t)\right)^2,\ \theta\in\mathbb{R}^N$$

Mismatch between simulation results and field measurements.



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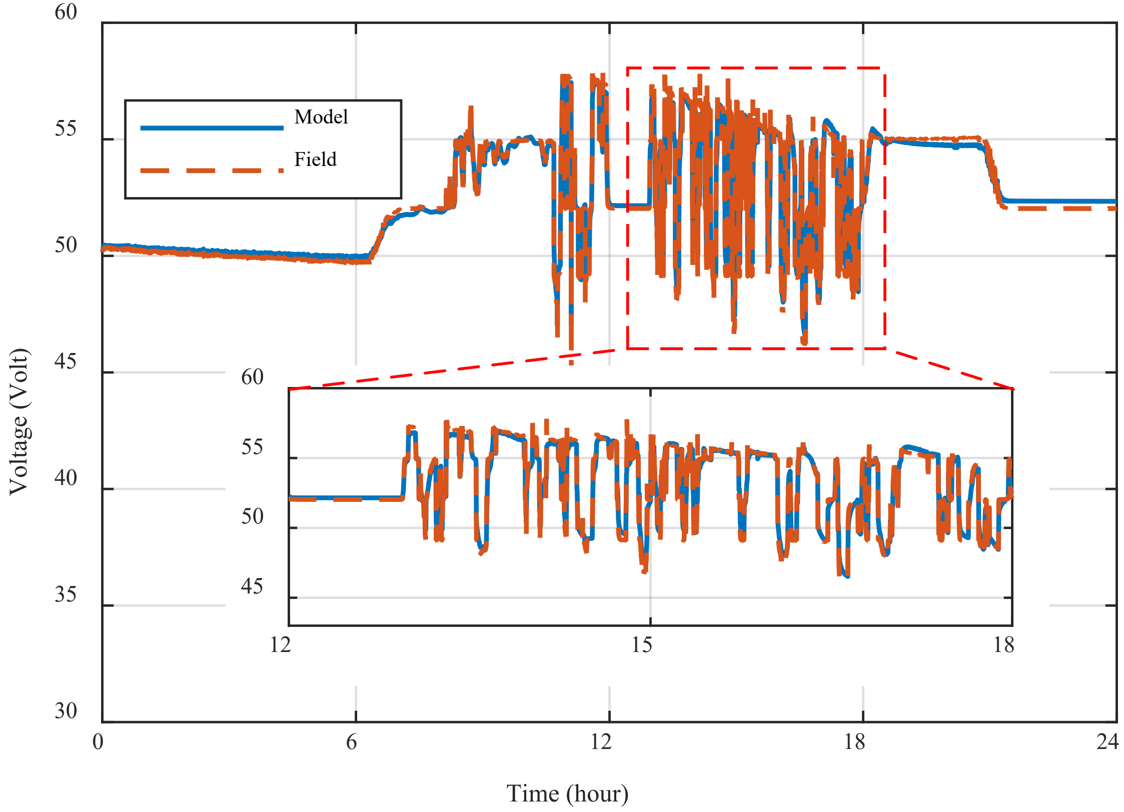
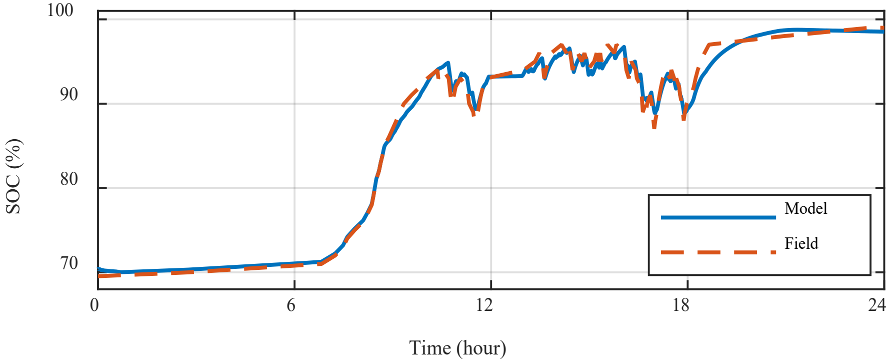
Modeled Outputs and Field Measurements

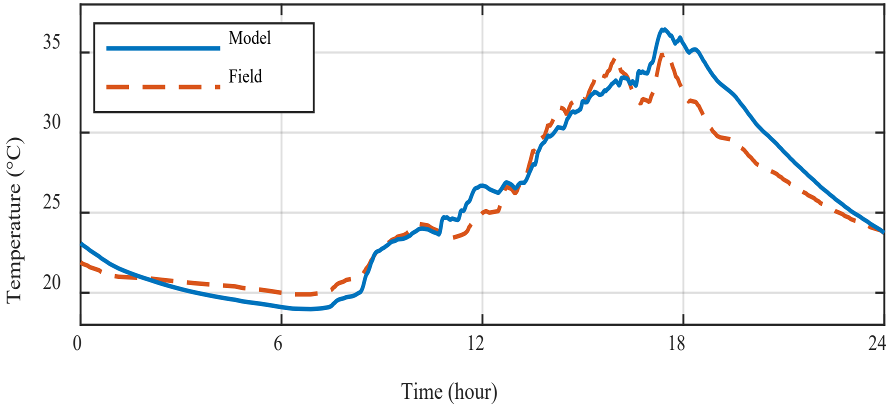
Terminal Voltage



State-of-charge



Battery Temperature



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Battery System Model

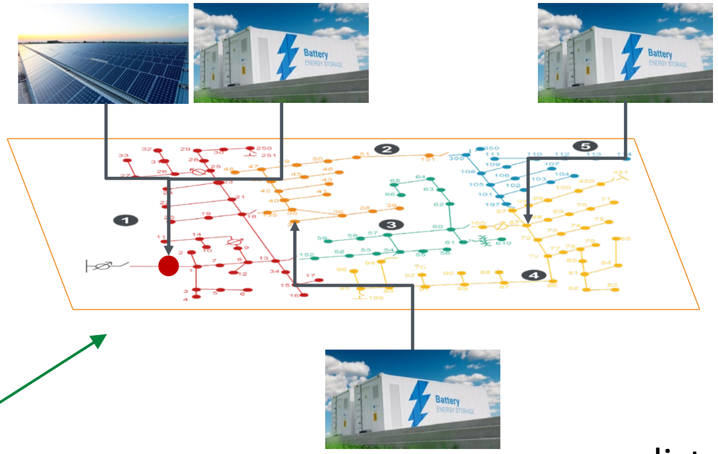
Battery Control System Modeling

Battery Operation Modes

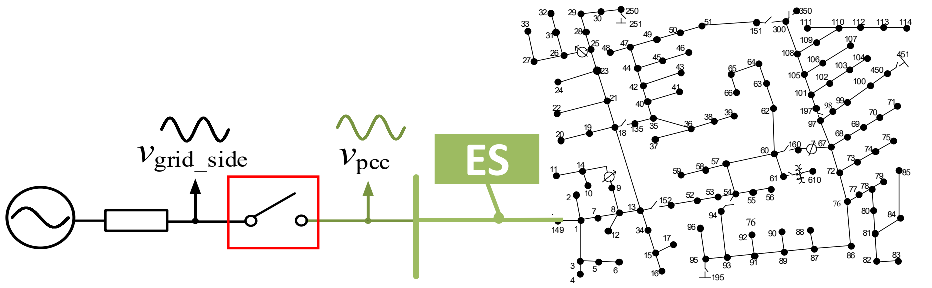
Module	Operation mode	Functionality	Requirement
Battery Energy Storage Model (BESS)	Grid-forming mode	Voltage and frequency regulation	It's responsible for regulating PCC voltage and setting the system frequency.
		Three-phase imbalance control	If the distribution grid is imbalanced, ES should quickly readjust its output voltage to maintain voltage balance.
		Current limiting control	The inverters must be protected from overcurrent of the semiconductor devices in overload and fault cases.
		Coordinated voltage regulation with multiple ES units	If there are multiple ES units are connected into the distribution grid and worked as grid-forming mode, PCC voltage can be regulated using the centralized secondary control.
		Resynchronization	In order to connect the MG to the grid, the phase and amplitude voltage between the grid and the MG will be regulated as an equal value using the synchronization control loop.
	Grid-following mode	Real and reactive power dispatch	In grid-tied or grid-following mode, the model should make the output power of the inverter follow the reference values and maintain the voltage reference tracking.
		Disturbance ride-through	When working in the grid-following mode, the machine will trip if the grid's voltage or frequency goes beyond the specified limits.

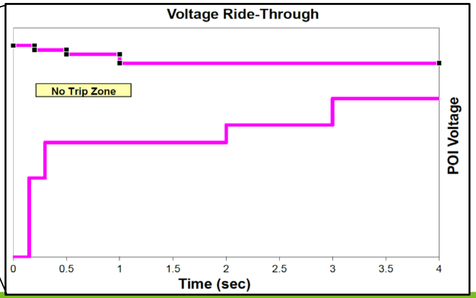
One battery storage unit

Multiple battery storage units



distribution grid



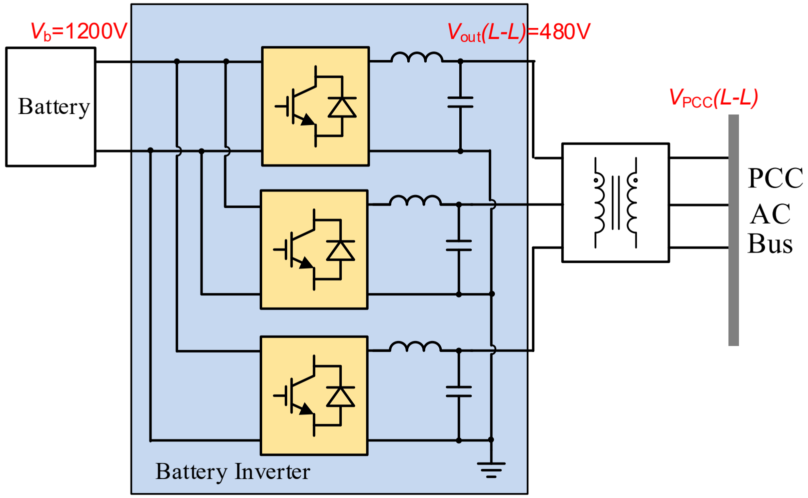


NERC PRC-024-2

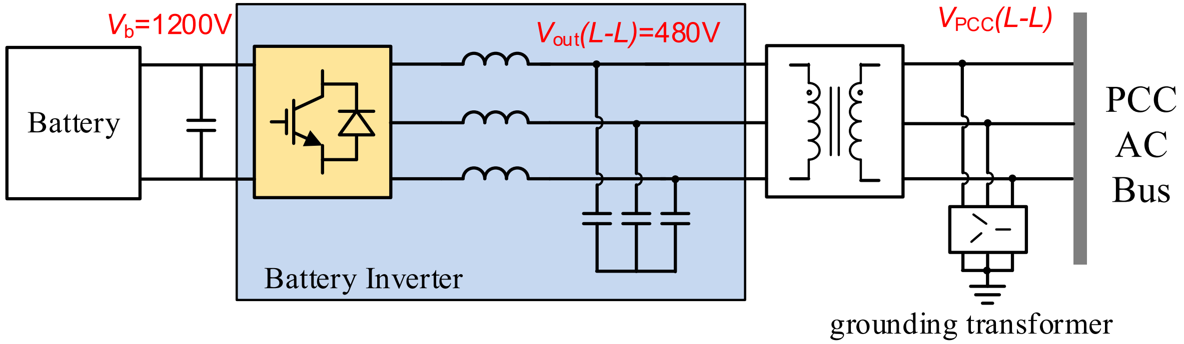
Bei Xu, Victor Paduani, Hui Yu, David Lubkeman, and Ning Lu, "A Novel Grid-forming Voltage Control Strategy for Supplying Unbalanced Microgrid Loads Using Inverter-based Resources," published to 2022 PES General meeting. Available online at: https://arxiv.org/pdf/2111.09464.pdf

Batter System Topology

	Three Single-Phase Inverter Model	Three-phase Inverter Model
Characteristic	Separate circuit and controllers for each phase.	Integrated circuit and controller.
Application	Mostly used in the residential applications and for running lower power loads.	Mostly used in large industries and for high power applications.
Grid-forming mode	BESS power limitation for unbalance regulation: $\lvert P_a \rvert$, $\lvert P_b \rvert$, $\lvert P_c \rvert \leq P_{rated}$	BESS power limitation for unbalance regulation: 1) power unbalance factor* ≤ 0.6; 2) $\lvert P_a \rvert$, $\lvert P_b \rvert$, $\lvert P_c \rvert \leq 0.95\ P_{rated}$
Grid-following mode	Output power for each phase is controllable.	Output power can't be controlled per phase



Three Single-phase Inverter Model



Three-phase Inverter Model

Bei Xu, Victor Paduani, Hui Yu, David Lubkeman, and Ning Lu, "A Novel Grid-forming Voltage Control Strategy for Supplying Unbalanced Microgrid Loads Using Inverter-based Resources," published to 2022 PES General meeting. Available online at: https://arxiv.org/pdf/2111.09464.pdf

Voltage Control for Unbalanced Loads

- The voltage reference of the inner voltage controller, v_o^*, is generated based on the conventional droop and secondary control **without the need for the decomposition of the positive-sequence and negative sequence components**.
- **Inner voltage controller** design: ***αβ*** stationary reference frame (SRF)-based inverter controller.
- Add a **grounding transformer** in the circuit to mitigate the impact of **zero-sequence** currents on voltage regulation.

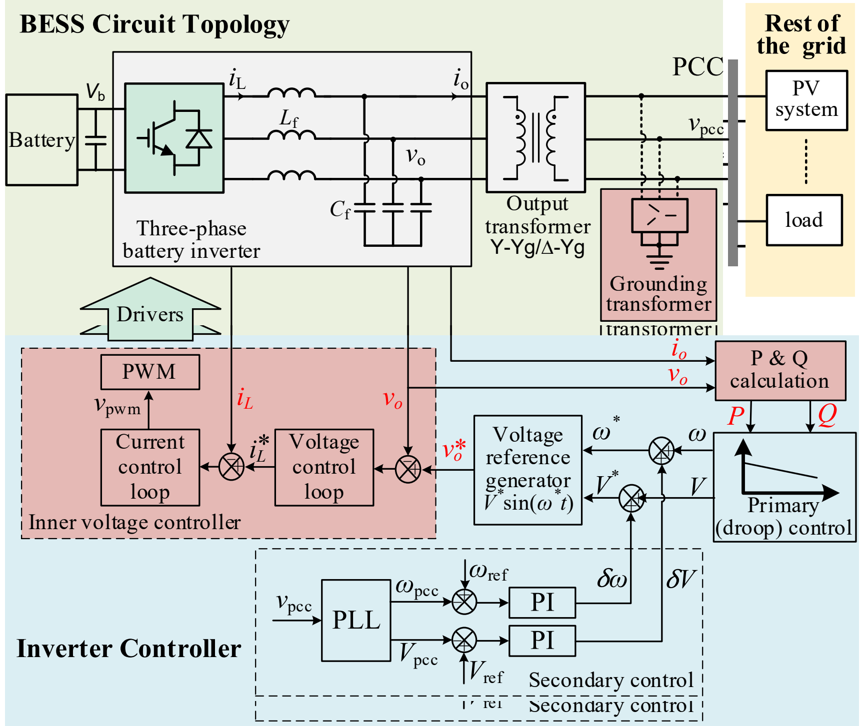
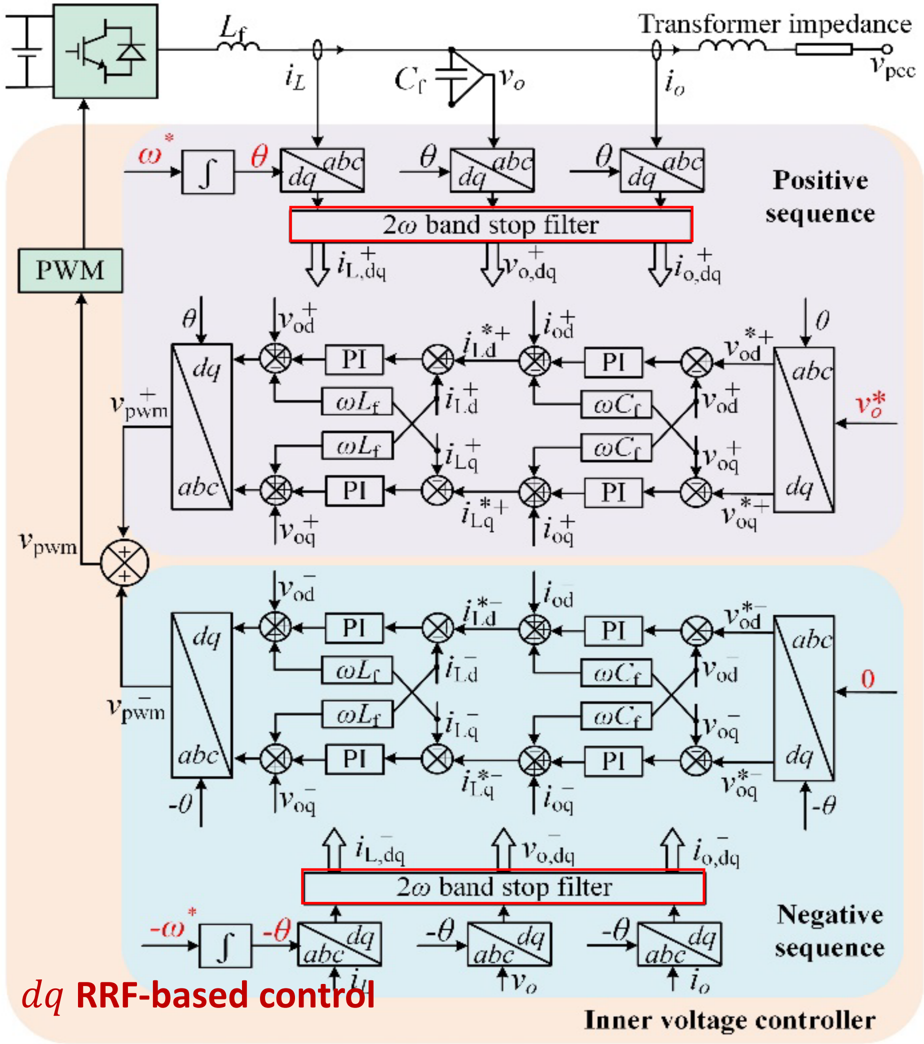
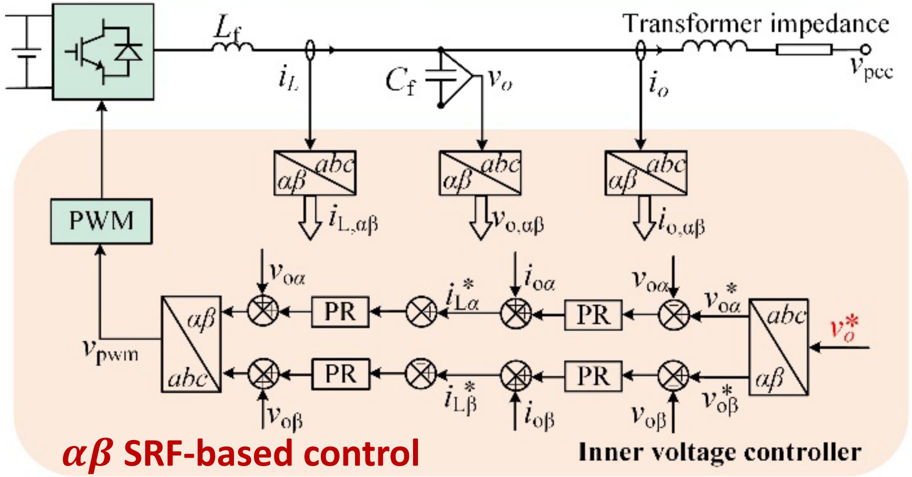


Fig. Topology and control structure of the three-phase grid-forming BESS

Bei Xu, Victor Paduani, Hui Yu, David Lubkeman, and Ning Lu, "A Novel Grid-forming Voltage Control Strategy for Supplying Unbalanced Microgrid Loads Using Inverter-based Resources," published to 2022 PES General meeting. Available online at: https://arxiv.org/pdf/2111.09464.pdf

Comparing dq and $\alpha\beta$ Controllers





- A dual-reference control scheme, dq^+ and dq^-, rotates in the opposite direction.
- **Band-stop filters** are used to reject double-frequency (2ω) components →→ introduces filter delay and **slows down the convergence** of the output phase angle.

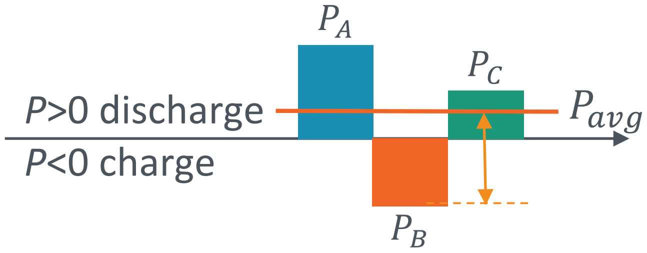
All the measured voltage and current are directly transformed from abc to $\alpha\beta$ coordinates, the **computational burden** is greatly **simplified**.

Bei Xu, Victor Paduani, Hui Yu, David Lubkeman, and Ning Lu, “A Novel Grid-forming Voltage Control Strategy for Supplying Unbalanced Microgrid Loads Using Inverter-based Resources,” published to 2022 PES General meeting. Available online at: https://arxiv.org/pdf/2111.09464.pdf

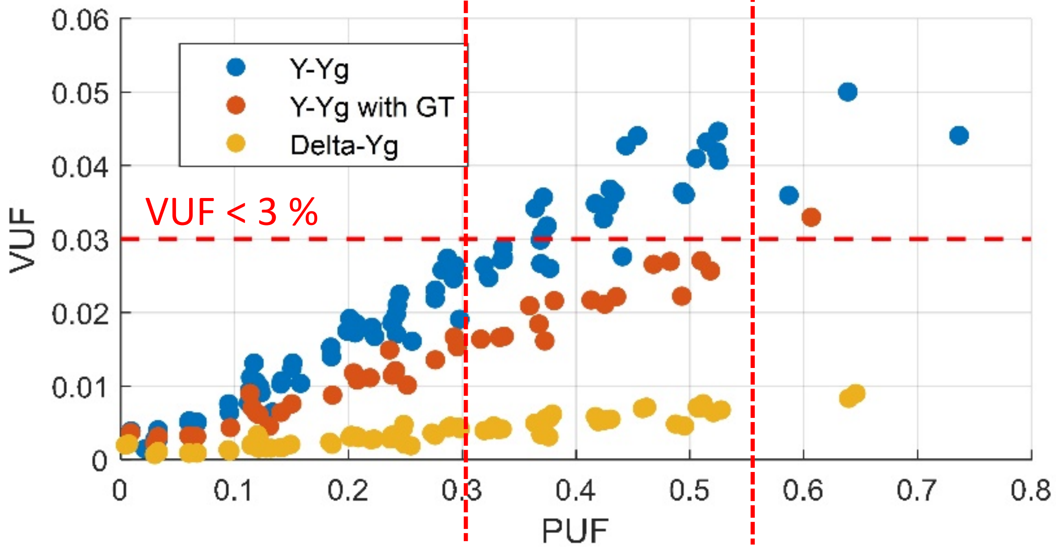
Regulate 3-phase Unbalance Loads

Voltage unbalance factor (VUF) $VUF = \sqrt{V_-^2 + V_0^2}/|V_+|$ [1] < 3 %

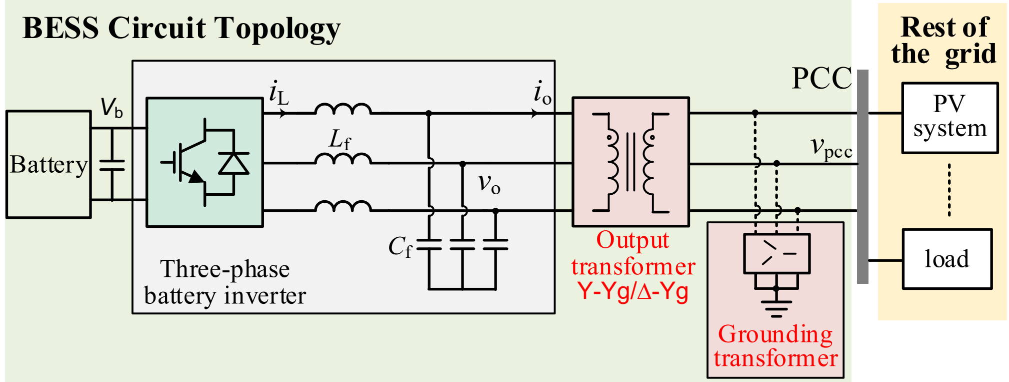
Power unbalance factor (PUF) $PUF = \frac{Max(|P_A - P_{avg}|, |P_B - P_{avg}|, |P_C - P_{avg}|)}{|P_{rated}|}$



Power-Voltage Unbalance Curves



PUF < 0.3 PUF < 0.55



If grounding transformer is added to the Y-Yg output transformer, VUF can be regulated within 3% when PUF 55% or less.

[1] F. Shahnia, P. J. Wolfs and A. Ghosh, "Voltage Unbalance Reduction in Low Voltage Feeders by Dynamic Switching of Residential Customers Among Three Phases," in IEEE Transactions on Smart Grid, vol. 5, no. 3, pp. 1318-1327, May 2014.

[2] Bei Xu, Victor Paduani, Hui Yu, David Lubkeman, and Ning Lu, “A Novel Grid-forming Voltage Control Strategy for Supplying Unbalanced Microgrid Loads Using Inverter-based Resources,” published to 2022 PES General meeting. Available online at: https://arxiv.org/pdf/2111.09464.pdf

Battery System Modelling Considerations

Power and Energy Management Needs
Dynamic Response versus Steady-state Perfromance

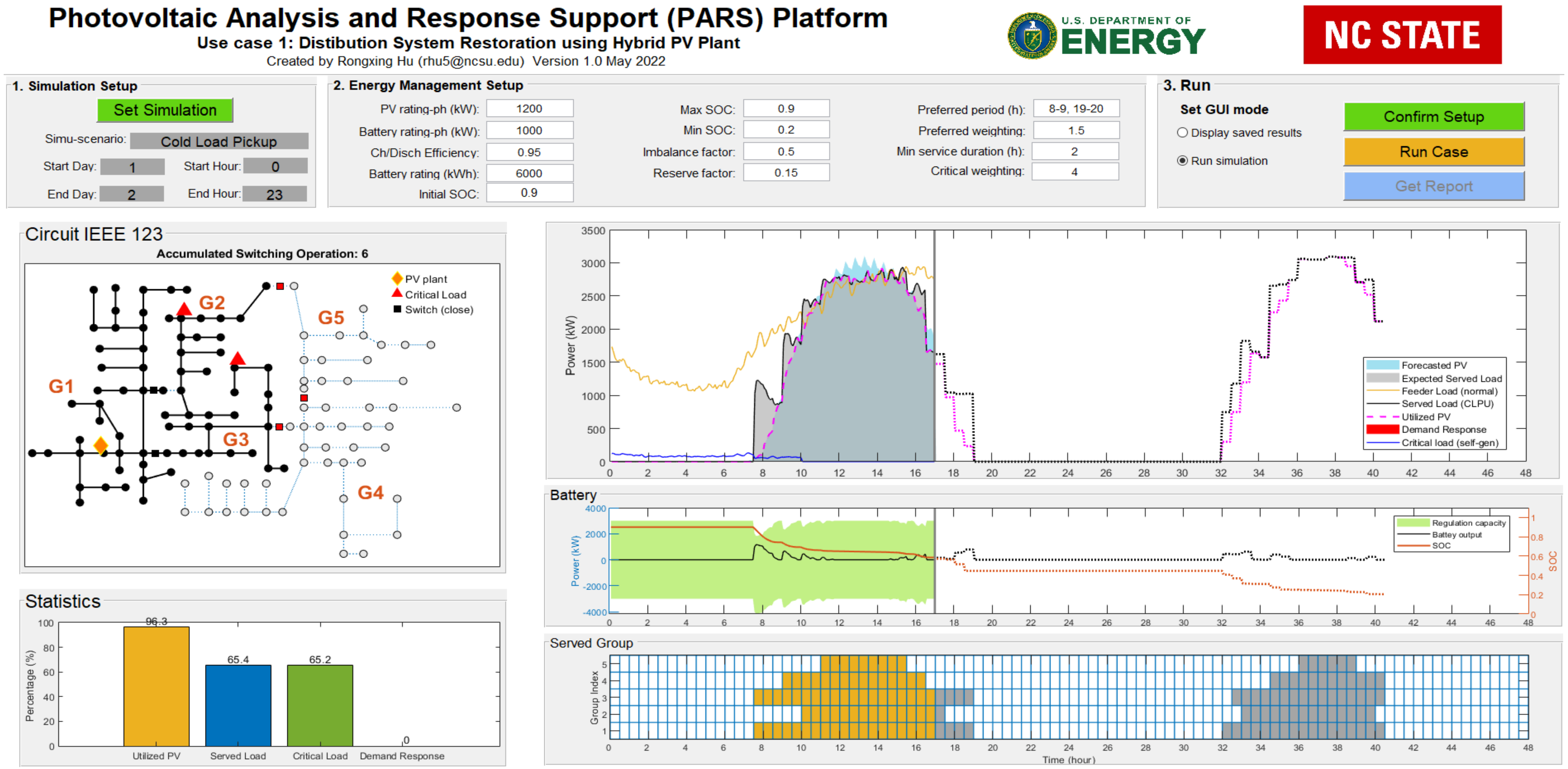
Meeting Power and Energy Management Needs

- Coping with PV and load forecasting errors and variations
  - 24-hour ahead forecasting errors → Energy Reserves
  - Hour-ahead needs → Power Reserves
  - Minute-by-minute power fluctuations → Ramp needs
  - Instantaneous power fluctuations → Frequency and voltage regulation nees
- Coping with unbalanced loads
- Coordination among different grid-forming resources
  - Grid-forming
  - Grid-following
  - Grounding transformers

Differences between Results

	Considering System Dynamic Responses	Considering only Steady-State Responses
Duration	Within a week	Weeks to years
Time Steps	Micro-second or millisecond	A few seconds, minutes, and above
Control Systems	Device-level controller modeled	Power and Energy Management
Communication	Impacts of delays, losing data packages, etc.	Long-duration communication outages
Stability	System voltage and frequency can go unstable	Frequency is usually not modeled; can model quasi-steady state voltage violations
Coordination	Real-time coordination	5-, 15-, 60- minute
Life-time/degradation	No, but can provide operational statistics	Yes
Cost/benefit Study	Can provide validation results for critical operation conditions	Yes (but cannot guarantee the system can cope with all dynamic operation conditions)
…		

Considering only Steady-State Responses



Photovoltaic Analysis and Response Support (PARS) Platform
Use case 1: Distibution System Restoration using Hybrid PV Plant
Created by Rongxing Hu (rhu5@ncsu.edu) Version 1.0 May 2022

1. Simulation Setup
Simu-scenario: Cold Load Pickup
Start Day: 1
Start Hour: 0
End Day: 2
End Hour: 23

2. Energy Management Setup
PV rating-ph (kW): 1200
Battery rating-ph (kW): 1000
Ch/Disch Efficiency: 0.95
Battery rating (kWh): 6000
Initial SOC: 0.9
Max SOC: 0.9
Min SOC: 0.2
Imbalance factor: 0.5
Reserve factor: 0.15
Preferred period (h): 8-9, 19-20
Preferred weighting: 1.5
Min service duration (h): 2
Critical weighting: 4

3. Run
Set GUI mode
○ Display saved results
● Run simulation

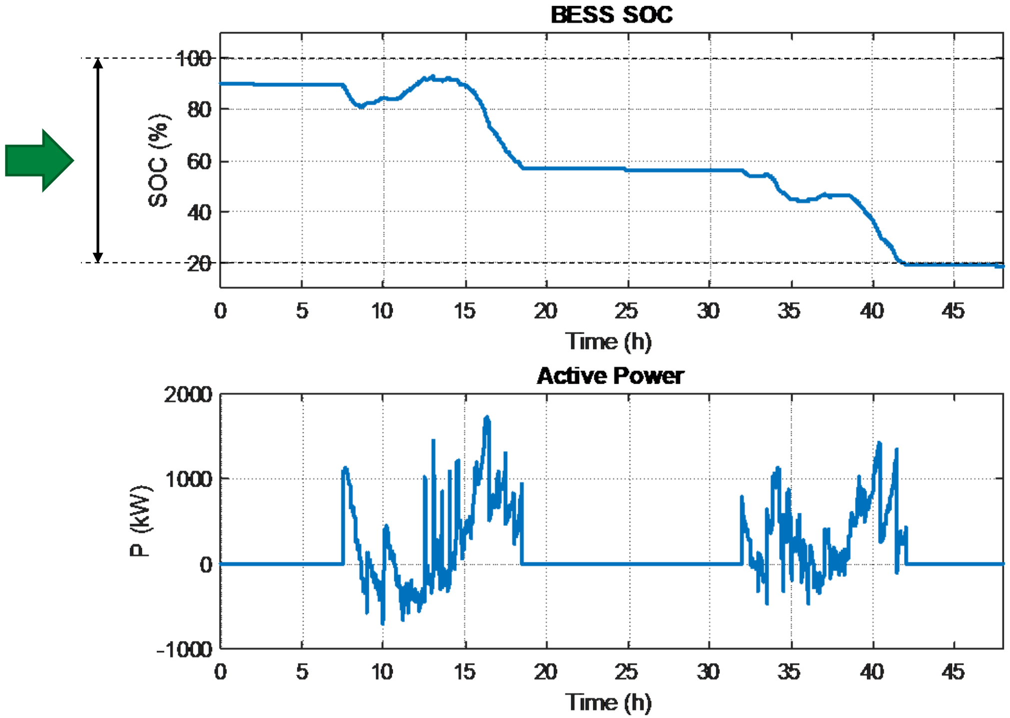
Circuit IEEE 123
Accumulated Switching Operation: 6

Scan to view the demos

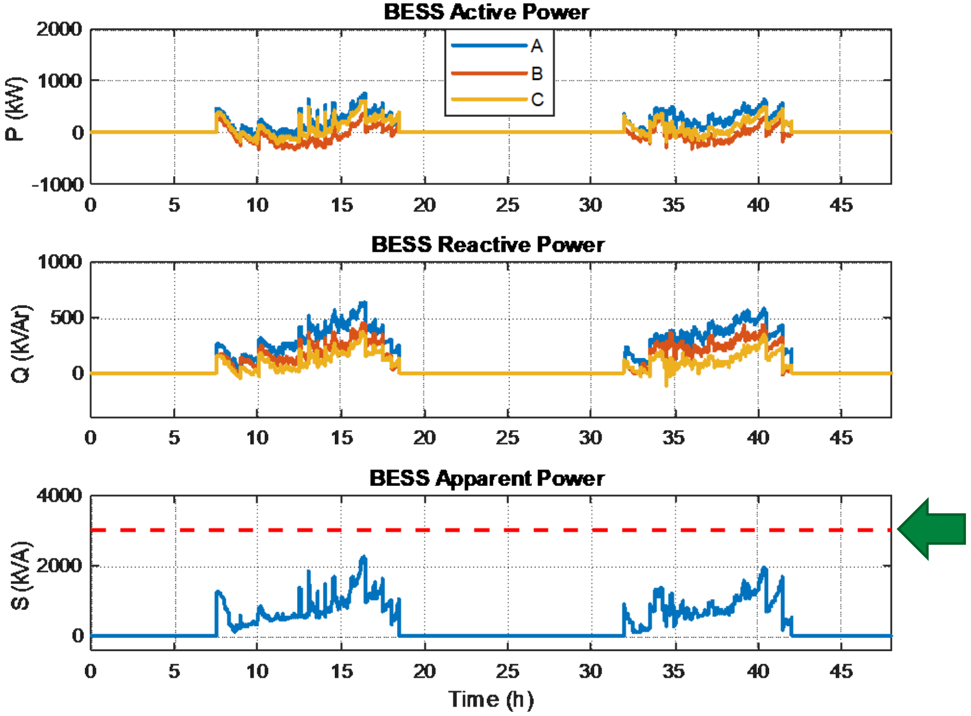
Rongxing Hu, Yiyan Li, Si zhang, Valliappan Muthukaruppan, Ashwin Shirsat, Mesut Baran, Wenyuan Tang, David Lubkeman, Ning Lu, "A Load Switching Group based Feeder-level Microgrid Energy Management Algorithm for Service Restoration in Power Distribution System", *Proc. of IEEE PES 2021 General Meeting*. 2021. Available online at:https://arxiv.org/abs/2011.08735

Battery Operation Considering Dynamic Responses

- BESS maintains SOC within acceptable range of 20 - 100%.
- BESS output apparent power does not violate 3 MVA ratings through the restoration process.
- Note that if battery does not have sufficient reserve, simulation can be terminated due to lack of frequency and voltage regulation capabilities.



BESS SOC and active power



BESS output power

Conclusions

- A **digital-twin based cost-benefit study procedure** can be as follows:
  - Develop grid support functions using faster-than-real-time simulation tools (**steady-state**)
  - Test and validate performance on real-time simulation platforms (**dynamic responses**)
  - Coordination between system-level and device-level controllers considering **communication links**
  - Co-simulate transmission-distribution to **scale-up the study**
- **High-fidelity Digital Twins** are important for developing new grid support functions
  - **Benefits:** compared with field tests, testing on digital twins are safer, cheaper, faster, and scalable
  - **Challenges**: Data requirements are high (require realistic network topologies; require PV and load data sets for populating the network models; require manufacture data sheets; require field tests for benchmarking the model dynamic responses; ….)