SOLAR ENERGY
TECHNOLOGIES OFFICE
U.S. Department Of Energy

A Photovoltaic (PV) Analysis and Response Support (PARS) platform

EE0008770 managed by David Walter

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Prepared for the DOE Transients, Dynamics Modeling and Analytics Webinars
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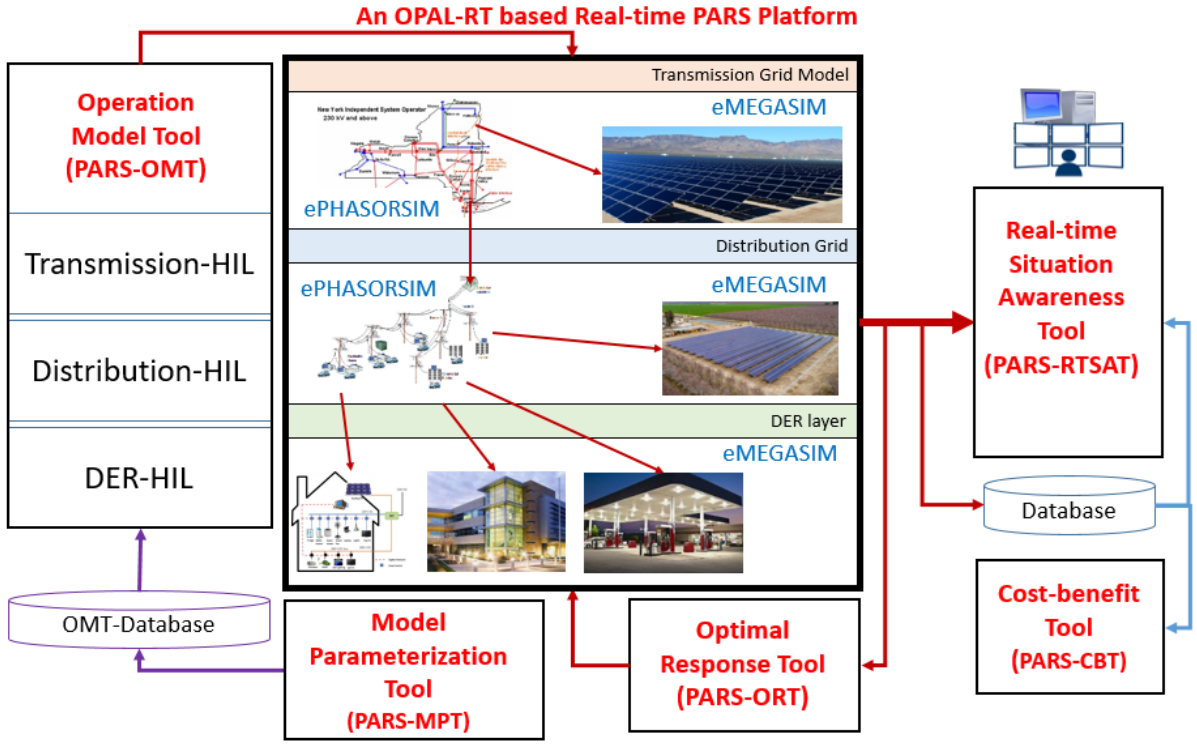
NC STATE UNIVERSITY | FREEDM SYSTEMS CENTER | GridWrx Lab

Background

- An Overview of the PARS Project

Project Summary

The objective of this project is to develop **a Photovoltaic (PV) Analysis and Response Support (PARS) platform** that provides real-time situational awareness and optimal response plan selection. By binding steady-state and dynamic simulation and integrating faster-than-real-time simulation into real-time simulation, the PARS operation platform can be used to emulate, monitor, and develop optimal response plans for hybrid PV systems locate at transmission, distribution, all the way down to behind-the-meter (BTM) customer sites in both normal and emergency operations. When running off-line using historical data, PARS can also be used as a planning platform to design and test PV-based grid support functions and perform cost-benefit studies.



Key Personnel/Organizations

PI: Ning Lu (North Carolina State University)

Key Personnel: David Lubkeman, Srdjan Lukic, Mesut Baran, Wenyuan Tang, Isaac Panzarella (North Carolina State University); Nader A Samaan and Mallikarjuna R Vallem (Pacific Northwest National Lab); Xia Jiang and George Stefopoulos (New York Power Authority); Laura Kraus and Roger Willardson (Strata Solar); Marshall Cherry (Roanoke Electric Cooperative); PJ Rehm (ElectriCities); Paul Darden (Wilson Energy); Edmond Miller and Matt Makdad (New River Light&Power)

Key Milestones & Deliverables

Year 1:	Prototype PARS running on OPAL-RT using benchmark IEEE test systems
Year 2:	PARS running on OPAL-RT on NYPA 500-bus system and on realistic distribution feeder models
Year 3:	Three demonstration PARS running on NYPA, Strata Solar and NCSU sites

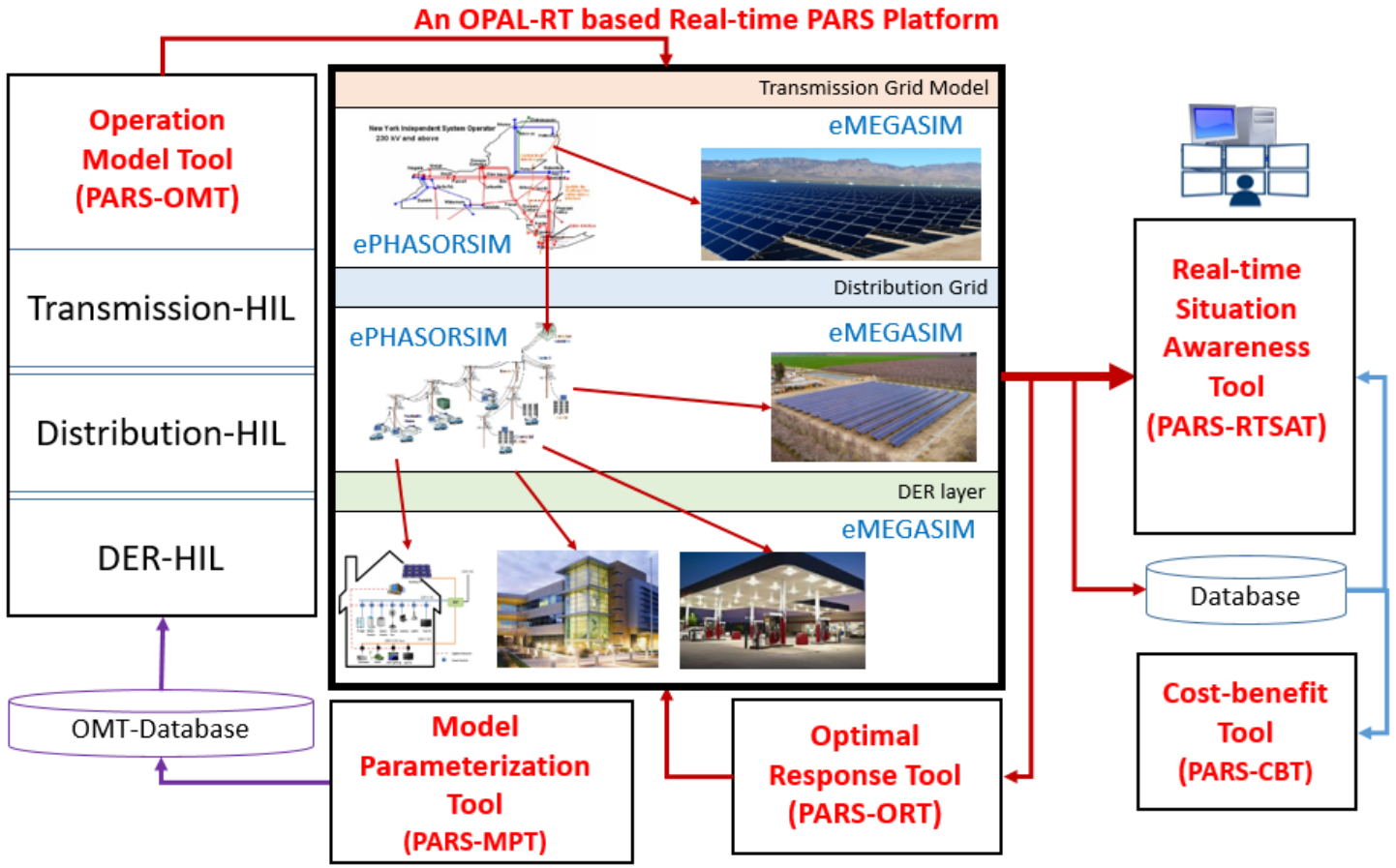
Project Impact

The expect outcome of this project is to bring the performance of the hybrid PV systems to be on a par with those of flexible generation resources in the following four performance areas when providing grid support functions (GSFs): visibility, dispatchability, security, and reliability.

Technical Objectives and Deliverables

Objective: Develop *a* ***Photovoltaic (PV) Analysis and Response Support (PARS) platform*** *as a power grid digital twin* that provides **real-time situational awareness** and **optimal response plan selection.**

Deliverables: A **functional prototype** of the PARS platform



Technical Objectives and Deliverables

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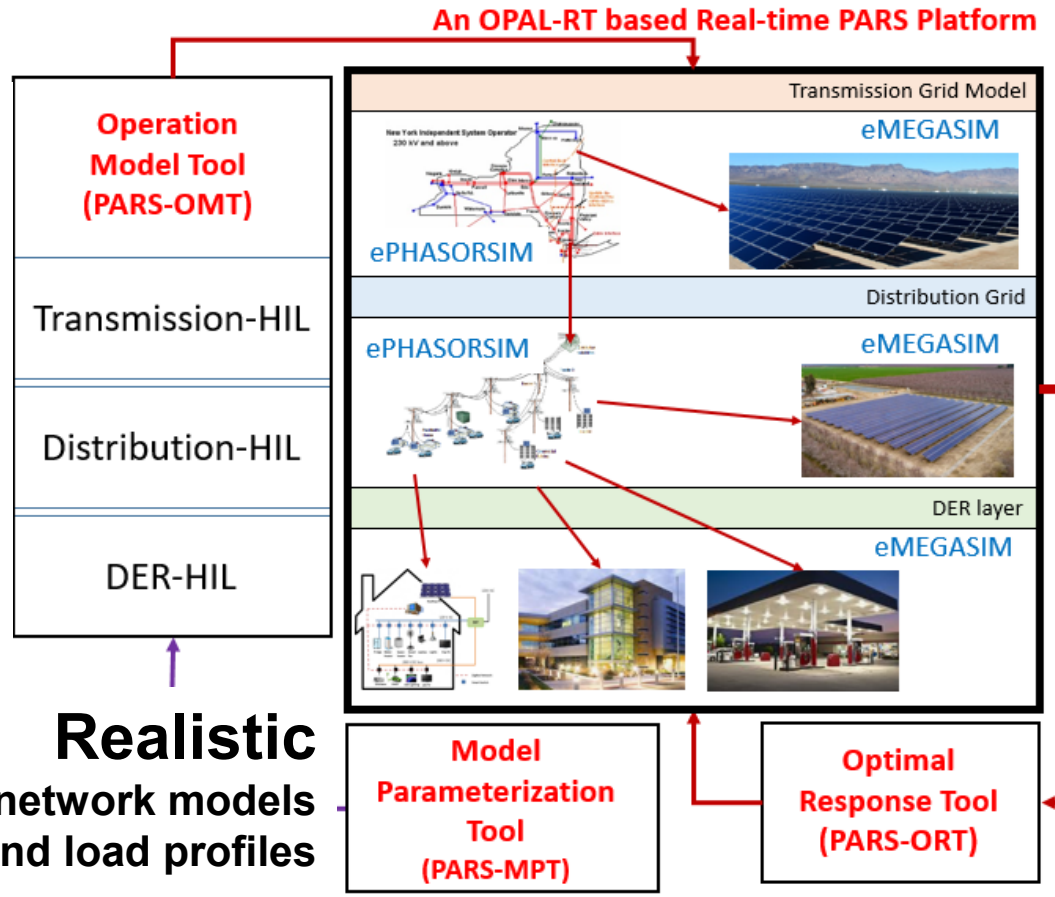


Real-time Situation Awareness Tool (PARS-RTSAT)

Database

Highly Scalable High Fidelity Nested

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

Realistic

Realistic network models
Time-series PV and load profiles

Visibility

Machine Learning enhanced forecasting

Secure by Design

Response Options

Faster-than Real-time

Functions Developed in Year 1 and Year 2

2 conference papers published
1 conference paper under preparation

3 conference papers published
1 journal paper under 2nd round review
3 conference papers under preparation

1 journal paper published
1 journal paper under 2nd review
1 journal paper under preparation

PNNL Transmission GSF Development

- Range: transmission level PV farms (100 MW +)
- Two main grid support functions: Black-start Sequence Control and Volt-var Control during restoration
- Benchmarked on the IEEE 118-bus test system
- Testing and validating on the NYISO system

PNNL HIL Test Systems and Integration

- Developed PV farm and energy storage system models
- Implemented blackstart sequence control
- Benchmarked on the IEEE-118 bus test system
- Benchmarking on the NYISO network model

NCSU Distribution GSF Development

- Range: kW - 50 MW
- Benchmarked on the IEEE-123 bus test system using realistic load and PV data
- Developed energy scheduling and power dispatch for residential and commercial roof-top PV systems and MW-level utility-scale PV farms supported by battery storage systems
- Coverage: from 48- and 24- hour ahead to 5- minute ahead
- Outage periods: up to weeks
- Developed Use Cases 1-3 to demonstrate the developed grid support functions
- Considered forecasting errors
- Testing cold-load pick-up and black-start sequence
- Developing use cases 4, 5, and 6: considering combinations of PV system in a multi-feeder systems for optimal response tool development

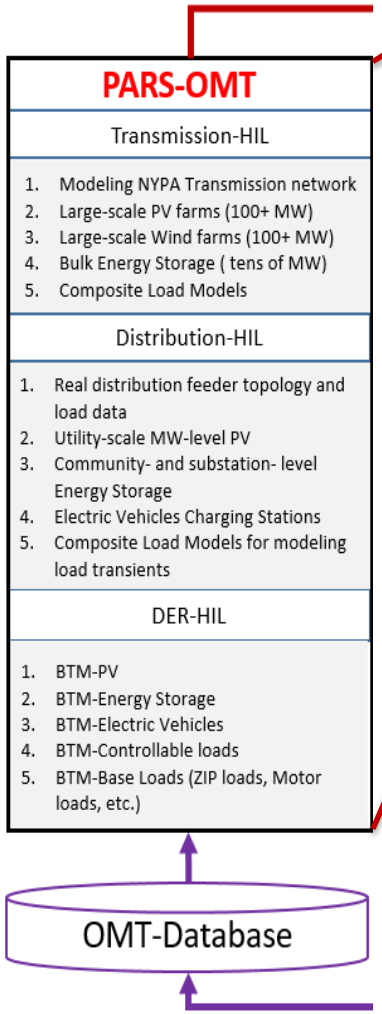
NCSU HIL Test Systems and Integration

- Developed PV (roof-top & PV farm), Diesel Generator, Battery, load, cold-load pickup model
- Device level controllers: Grid-forming and Grid-following functions
- Realistic communication protocols
- Benchmark on the IEEE-123 bus test system with actual smart meter data and PV farm data
- 24-hour and 48-hour real-time simulation for the 3 use cases
- Different event day types (cloudy, overcast, cold, hot, stormy)
- Communication system errors and cyber attack scenarios
- Benchmark on multiple-feeders and scale-up to sub-transmission-level

NCSU Situation Awareness

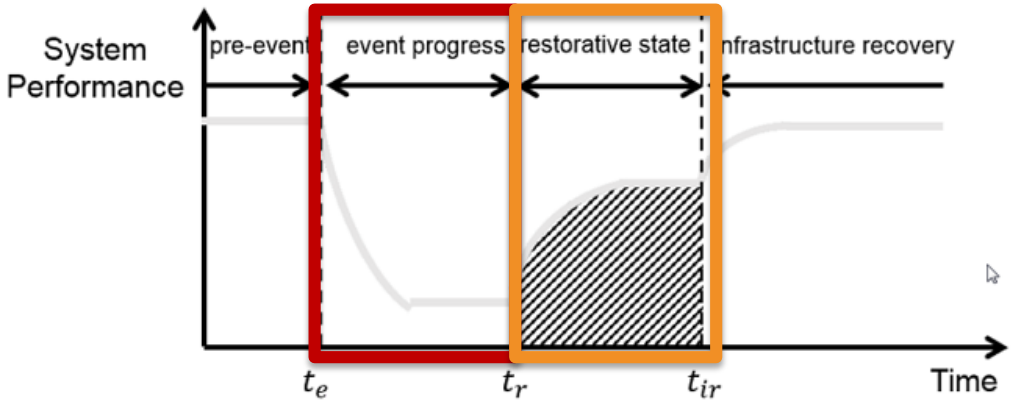
- Developed a general-purpose forecasting tool: meta-learning based load forecast for EMS at different load aggregation levels: multiple-look out windows, different load aggregation levels, variable forecasting horizons
- Developed TCN-based short-term PV forecasting tool for using detector-target sites forecasting sudden PV output changes
- Developed GAN-based method to convert low-resolution meter data to high-resolution data for the HIL test system to parameterize its load profiles
- Anomaly detection for communication system errors and cyber attacks

Main Grid Support Functions Considered in Distribution System Operation



Type of hybrid PV systems		Typical Size	Pre-fault	During fault			Restoration		Normal Operation		
			Resiliency Services						Grid Services		
			Fault-ride through	Islanding	Microgrid Operation	Reconfiguration	Black-start	Cold-load-pickup	Real Power Regulation	Reactive Power Regulation	Frequency Regulation
BTM PV	Residential	1-20 kW	✓		X			X	✓	✓	✓
	Commercial	<1MW	✓	✓	✓	✓	✓	✓	✓	✓	✓
PV Farms	Distribution	1-50 MW	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Transmission	50+ MW	X	X		✓	✓		✓	✓	✓

Main goal: Develop new grid support functions that corresponding to the **4-stage of resiliency services**



List of Publications - Published

Full Author List	Article Title	Journal/Conference
Li, Yiyan, Si Zhang, Rongxing Hu, and Ning Lu	A Meta-learning based Distribution System Load Forecasting Model Selection Framework	Applied Energy
F. Xie, C. McEntee, M. Zhang, B. Mather and N. Lu,	Development of an Encoding Method on an Co-simulation Platform for Mitigating the Impact of Unreliable Communication	IEEE transactions on smart grid
Q. Long, H. Yu, F. Xie, N. Lu and D. Lubkeman	Diesel Generator Model Parameterization for Microgrid Simulation Using Hybrid Box-Constrained Levenberg-Marquardt Algorithm	IEEE Transactions on Smart Grid
M. Liang, Y. Meng, J. Wang, D. Lubkeman and N. Lu,	FeederGAN: Synthetic Feeder Generation via Deep Graph Adversarial Nets	IEEE Transactions on Smart Grid
H. Yu, M. A. Awal, H. Tu, I. Husain and S. Lukic	Comparative Transient Stability Assessment of Droop and Dispatchable Virtual Oscillator Controlled Grid-Connected Inverters	IEEE Transactions on Power Electronics
Wang, Jiyu, Xiangqi Zhu, Ming Liang, Yao Meng, Andrew Kling, David L. Lubkeman, and Ning Lu	A Data-Driven Pivot-Point-Based Time-Series Feeder Load Disaggregation Method.	IEEE Transactions on Smart Grid
Rongxing Hu, Yiyan Li, Si zhang, Valliappan Muthukaruppan, Ashwin Shirsat, Mesut Baran, Wenyuan Tang, David Lubkeman, Ning Lu	MW-level PV powered microgrid energy management	2021 PES General Meeting
Victor Paduani, Lidong Song, Bei Xu, Dr. Ning Lu	PV power tracking control for providing ancillary services	2021 PES General Meeting
Ashwin Shirsat, Valliappan Muthukaruppan, Rongxing Hu, Ning Lu, Mesut Baran, David Lubkeman, Wenyuan Tang	Community-level PV powered dynamic microgrid energy management	2021 PES General Meeting
Quan Nguyen, Mallikarjuna R. Vallem, Bharat Vyakaranam, Ahmad Tbaileh, Xinda Ke, Nader Samaan	Controlling PV hybrid system for Black start	2021 PES General Meeting
Ahmad Tbaileh, Mallikarjuna R. Vallem, Quan Nguyen, Xinda Ke, Nader A. Samaan, George Stefopoulos, Xia Jiang	Controlling PV hybrid system for Black start	2021 PES General Meeting
H. Yu, M. A. Awal, H. Tu, Y. Du, S. Lukic and I. Husain	A Virtual Impedance Scheme for Voltage Harmonics Suppression in Virtual Oscillator Controlled Islanded Microgrids	*2020 IEEE Applied Power Electronics Conference and Exposition*
Asmaa Alrushoud, Catie McEntee, and Ning Lu	A Zonal Volt/VAR Control Mechanism for High PV Penetration Distribution Systems	2021 PES General Meeting
Long Qian, Hui Yu, Fuhong Xie, Wenti Zeng, Srdjan Lukic, Ning Lu, and David Lubkeman	Microgrid Power Flow Control with Integrated Battery Management Functions	2020 PES General Meeting
A. Alrushoud and N. Lu	Impacts of PV Capacity Allocation Methods on Distribution Planning Studies	2020 T&D
Jiyu Wang, Ning Lu, Sen Huang, and Di Wu	A Data-driven Control Method for Operating the Commercial HVAC Load as a Virtual Battery	2019 PES General Meeting

List of Publications - Submitted

1. Yiyan Li, Lidong Song, Si Zhang, Laura Kraus, Taylor Adcox, Roger Willardson, Abhishek Komandur, and Ning Lu, “TCN-based Spatial-Temporal PV Forecasting Framework with Automated Detector Network Selection,” https://arxiv.org/abs/2111.08809. submitted to IEEE Trans. Sustainable Energy.
2. Lidong Song, Yiyan Li, and Ning Lu. "ProfileSR-GAN: A GAN based Super-Resolution Method for Generating High-Resolution Load Profiles." arXiv preprint arXiv:2107.09523 (2021). Submitted to IEEE Trans. Smart Grid, under 2st round review
3. Mingzhi Zhang, Xiangqi Zhu, and Ning Lu, “A Data-driven Probabilistic-based Flexibility Region Estimation Method for Aggregated Distributed Energy Resources,” Submitted to IEEE Trans. Smart Grid. https://arxiv.org/abs/2110.07406.
4. 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,” submitted to 2022 PES General meeting. https://arxiv.org/pdf/2111.09464.pdf
5. Victor Paduani, Bei Xu, David Lubkeman, Ning Lu, “Novel Real-Time EMT-TS Modeling Architecture for Feeder Blackstart Simulations,” submitted to 2022 IEEE PESGM. https://arxiv.org/pdf/2111.10031.pdf
6. Hanpyo Lee, Han Pyo Lee, Mingzhi Zhang,Mesut Baran, Ning Lu, PJ Rehm, Edmond Miller, Matthew Makdad P.E., “A Novel Data Segmentation Method for Data-driven Phase Identification,” submitted to 2022 PES General Meeting. http://arxiv.org/abs/2111.10500
7. Si Zhang, Mingzhi Zhang, Rongxing Hu, David Lubkeman, Yunan Liu, and Ning Lu, “A Two-stage Training Strategy for Reinforcement Learning based Volt-Var Control,” submitted to 2022 PES General Meeting. https://arxiv.org/abs/2111.11987

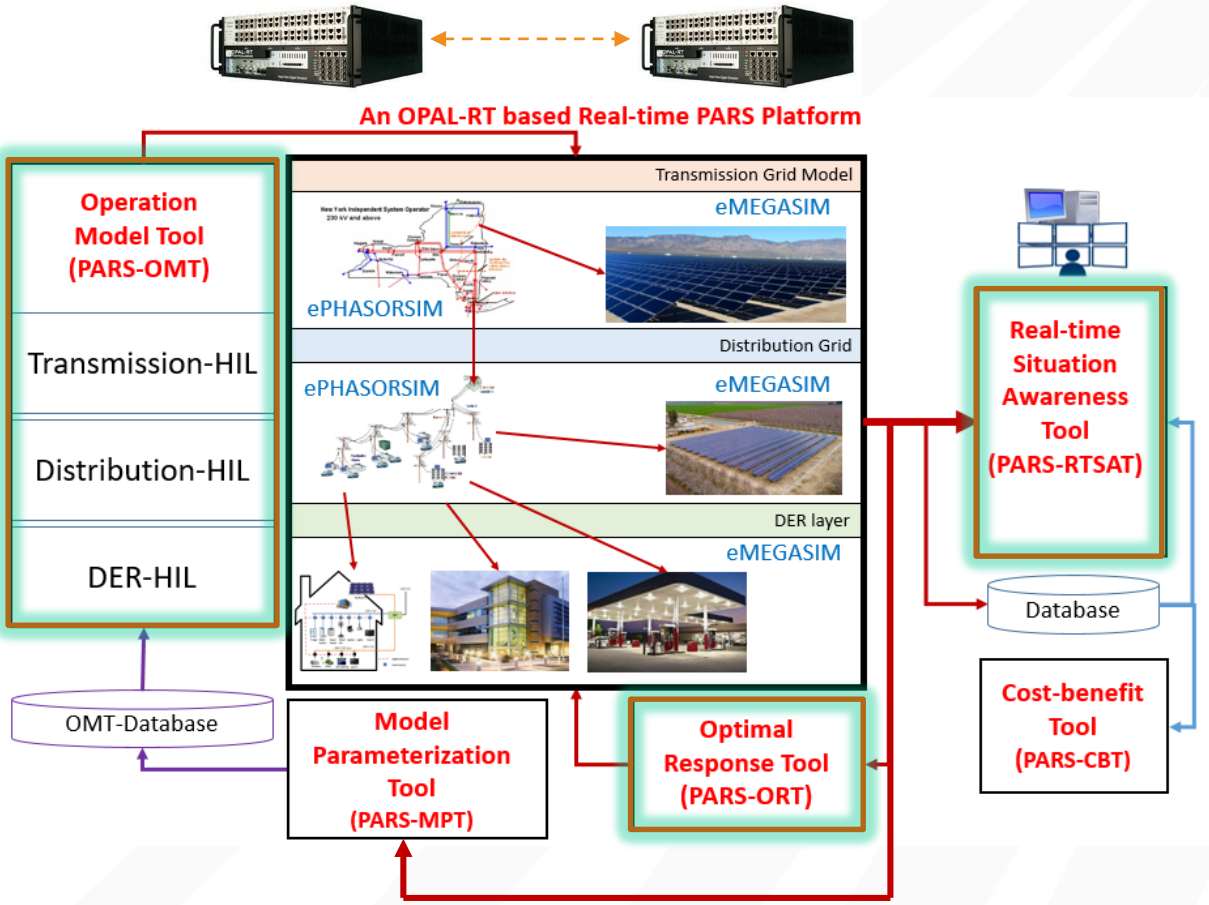
Content

- An Overview of the PARS Project
- An Overview of the PARS Platform

An overview of the PARS platform

1. PARS Real-time simulation platform

- Modeling the operation of **interconnected** physical systems in high-fidelity
- **Device-level control**: Grid-following and Grid-forming
- **Dynamics** when transition from one stead-state operation state to another
- **Obey** device and network **operational limits**
- **Communication** between the local and central controllers



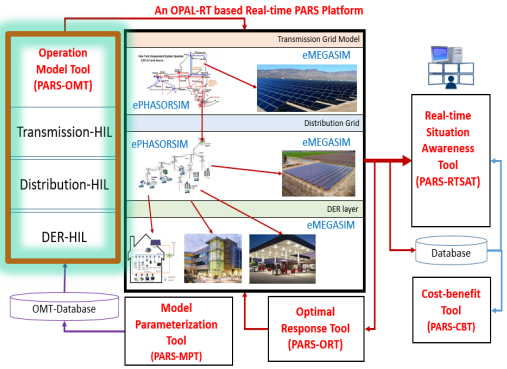
2. Situation Awareness Tool

- **Monitor** the current status
- **Authenticate** the data
- **Detect** anomalies
- **Forecast** the future

3. Faster-than-real-time Optimal Response Tool

- **System-level control**: energy and power management
- Response options (from 24-hour ahead to intra-hour)
- **Coordination**
- **Optimization**

PARS: A Network of High-fidelity Digital Twins



Topologies
- Transmission: IEEE-118 systems
- Distribution: IEEE-123 systems
- Modularized feeder topologies

Data Sources
- Actual data sets
- Synthetic data sets

Device Models
- Factory data sheets
- Field tests

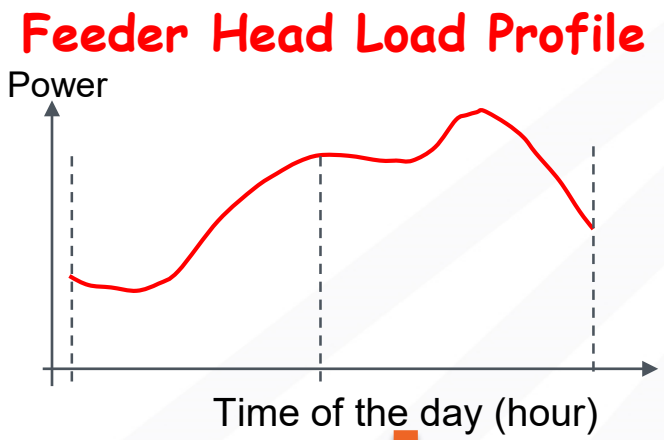
Use **faster-than-real-time** simulation on OPENDSS for algorithm development. (**Quasi-static** power flow runs, up to every 1-minute)

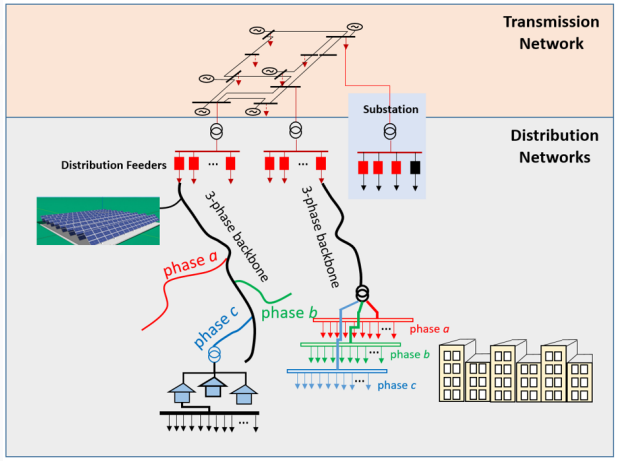
Use **real-time** simulation on OPAL-RT for testing and validation studies. (μs for modeling inverter based resources and ms for power flow calculations)

Developing PARS Digital Twins (1): In the past – No load diversity

In the past:

- Feeder head data is recorded at the substation
- Sub-nodes load profiles are not measured
- **Use the same load profile for all sub-nodes**





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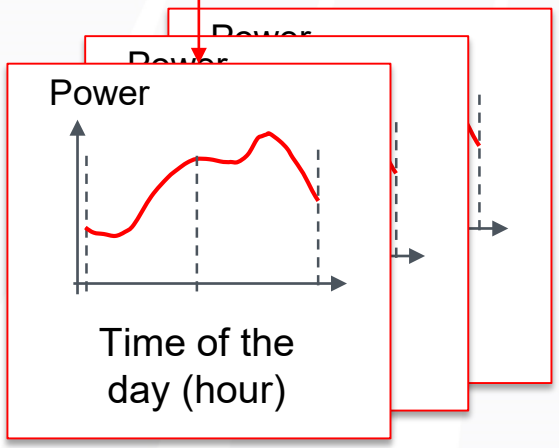
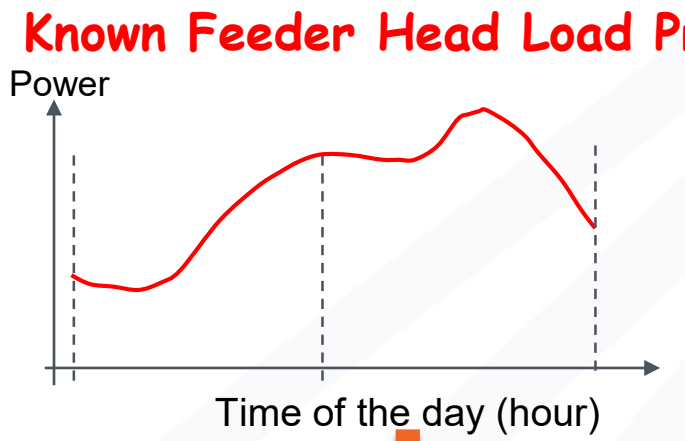
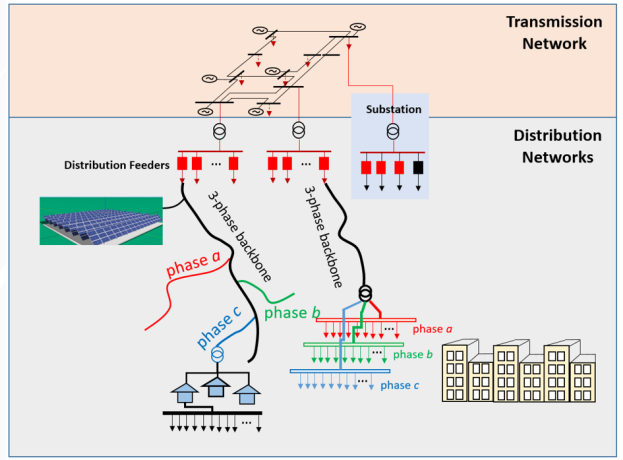


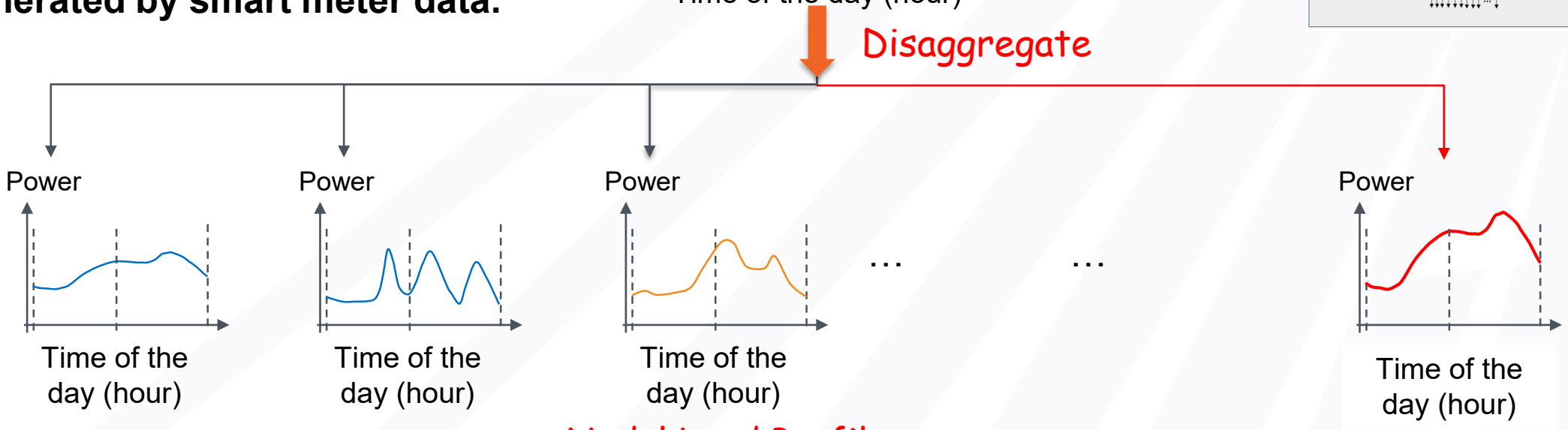
Developing PARS Digital Twins (2): Diversified Load Profiles

In the past: using the same load profile for all sub-nodes

Now: Diversified load profiles generated by smart meter data.

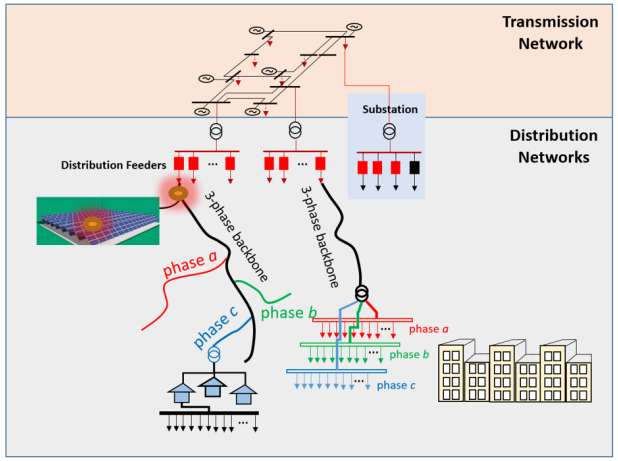


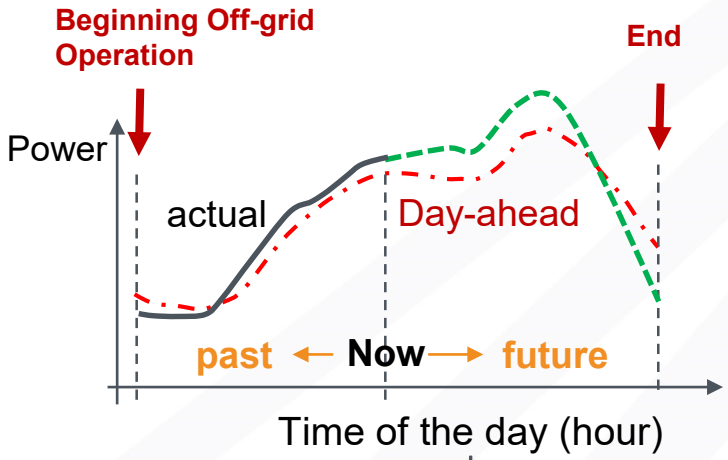




1. Wang, Jiyu, Xiangqi Zhu, Ming Liang, Yao Meng, Andrew Kling, David L. Lubkeman, and Ning Lu. "A Data-Driven Pivot-Point-Based Time-Series Feeder Load Disaggregation Method." *IEEE Transactions on Smart Grid* 11, no. 6 (2020): 5396-5406.
2. Ming Liang, Jiyu Wang, Yao Meng, Ning LU, David Lubkeman, and Andrew Kling. "A Sequential Energy Disaggregation Method using Low-resolution Smart Meter Data, " *Proc. of IEEE Innovative Smart Grid Technologies*, Washington DC, 2019.

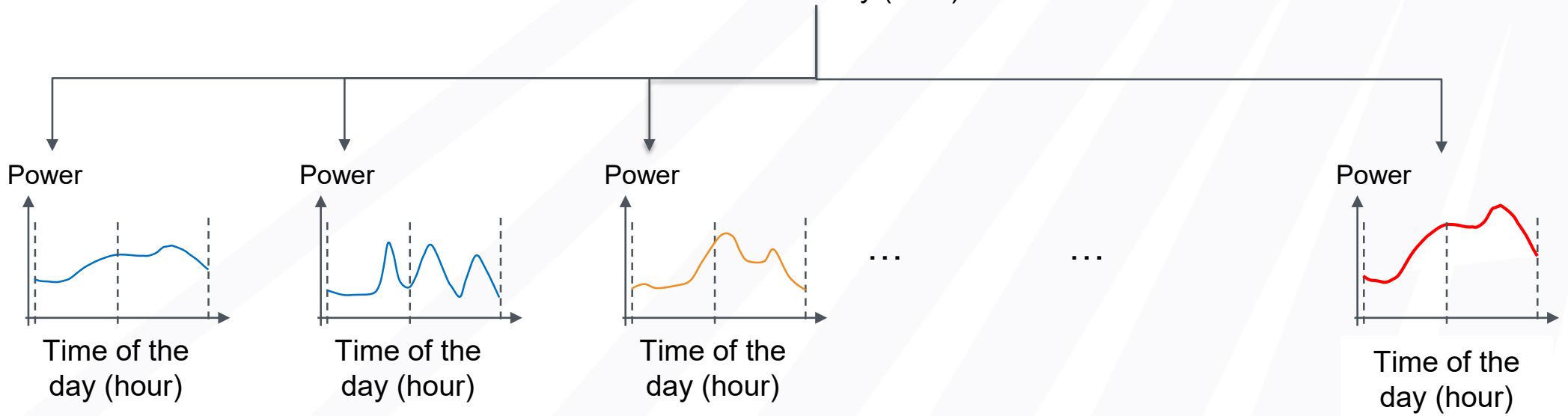
Developing PARS Digital Twins (2): Incorporate Day-ahead and Real-time Forecast for PV and Loads to Model Forecasting Errors





Situation Awareness Team:

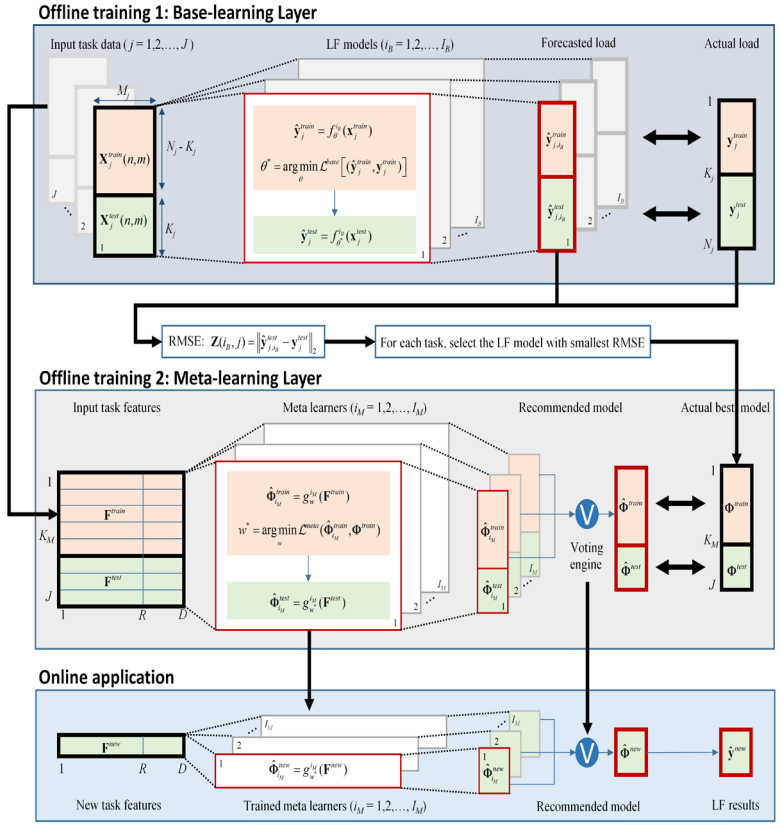
- Forecast PV and Load for the microgrid controllers
- Aggregated load profile
- For the entire outage horizon
- Updated hourly



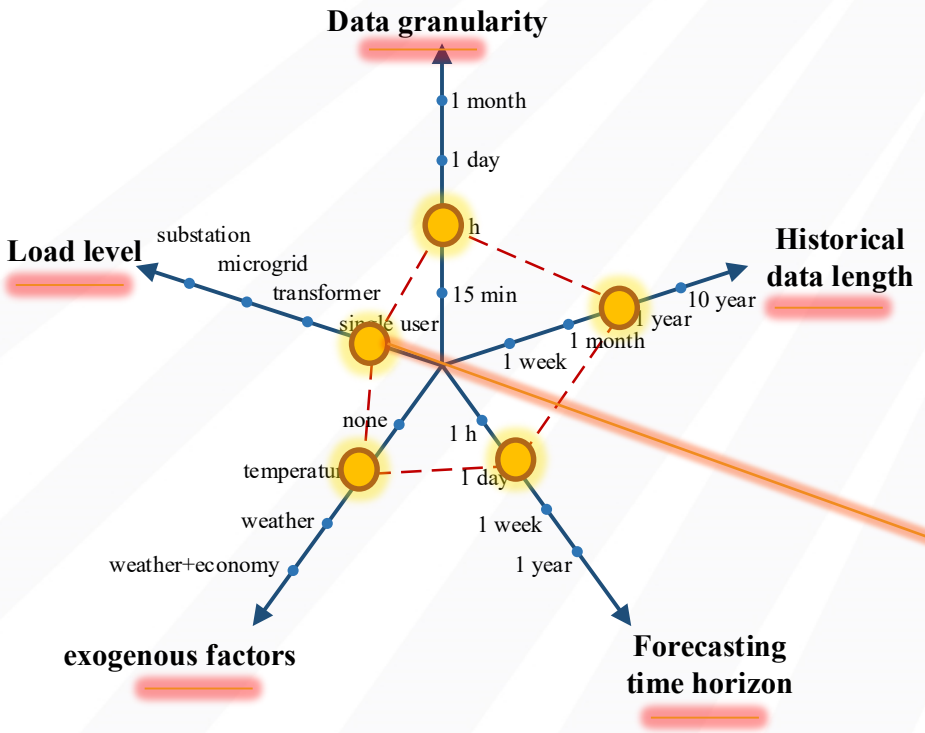
Li, Yiyan, Si Zhang, Rongxing Hu, and Ning Lu. "A Meta-learning based Distribution System Load Forecasting Model Selection Framework." *arXiv preprint arXiv:2009.12001* (2020). Accepted by Applied Energy. A brief introduction of the paper can be found in Youtube at: https://youtu.be/i8bUvGi9rC8

Situational Awareness (1): Meta-learning based Load Forecasting

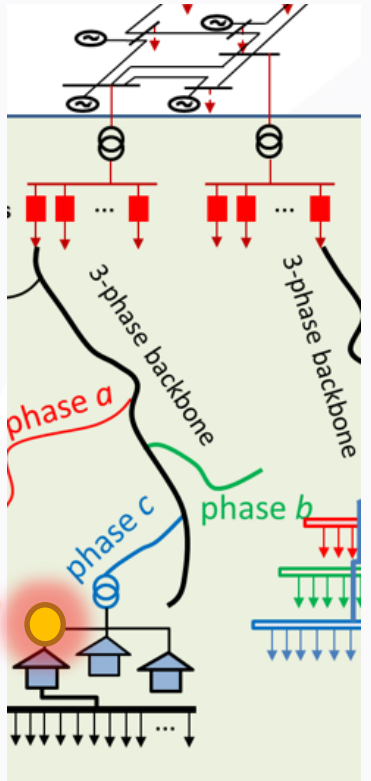
- Using **meta learning** to identify the best-fit forecasting model
- The framework is highly **automated** and **extendable**



Data source: Wilson Energy, Pecan Street



Handle heterogeneous forecasting tasks



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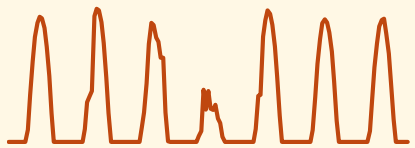
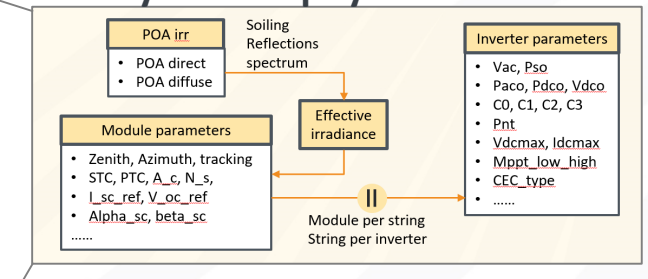
Situational Awareness (2): Spatial-temporal PV forecasting

A two-stage spatial-temporal forecasting framework: worked with **Strata Solar** for combining **physics-based** modeling and **deep-learning** modeling approaches to improve forecasting accuracy and robustness.

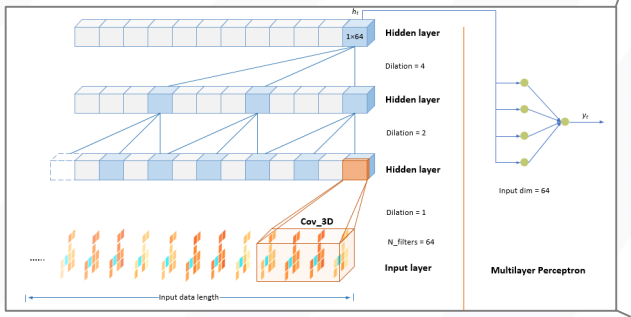
- In the **day-ahead stage**, physics-based models are built to achieve irradiance-power conversion.
- 1-7 days forecasting with hourly granularity.



Day-ahead: physics-based model

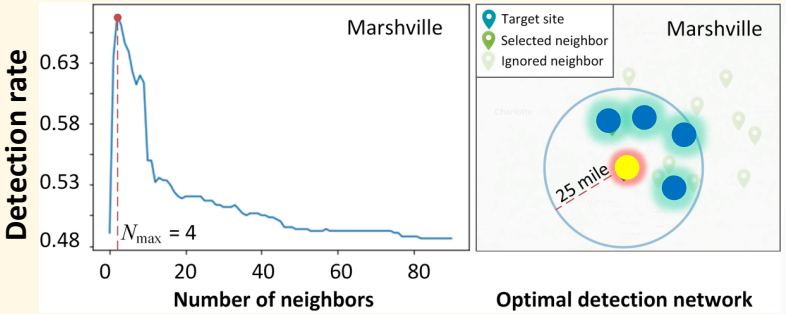


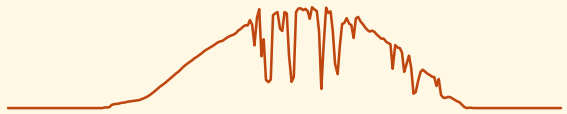
Real-time: spatial-temporal model



Data source: Strata Solar

- In the real-time stage, **detector selection algorithm** is proposed to identify the most correlated neighbors
- **TCN** is used to extract the spatial-temporal information and achieve forecasting





- Day-ahead stage can provide stable **operation baseline for** energy management
- Real-time stage can catch the **intra-hour PV variations** to support power management

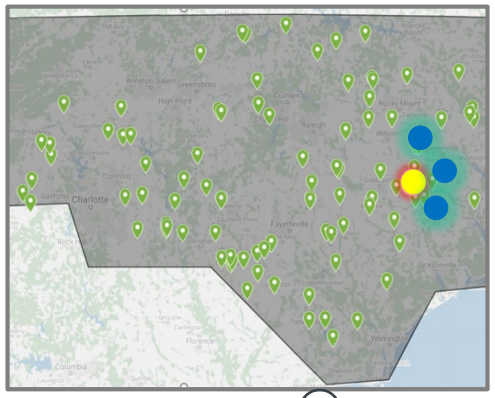
Yiyan Li, Lidong Song, Si Zhang, Laura Kraus, Taylor Adcox, Roger Willardson, Abhishek Komandur, and Ning Lu, "TCN-based Spatial-Temporal PV Forecasting Framework with Automated Detector Network Selection," https://arxiv.org/abs/2111.08809. submitted to IEEE Trans. Sustainable Energy.

Spatial-temporal PV forecasting - methodology

Using neighbors' data to improve real-time stage forecasting accuracy

① Code power output into matrix ② Select most correlated neighbors for the target site

③ Using **Temporal Convolutional Net (TCN)** to achieve forecasting



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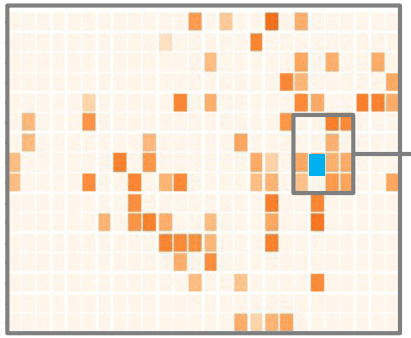

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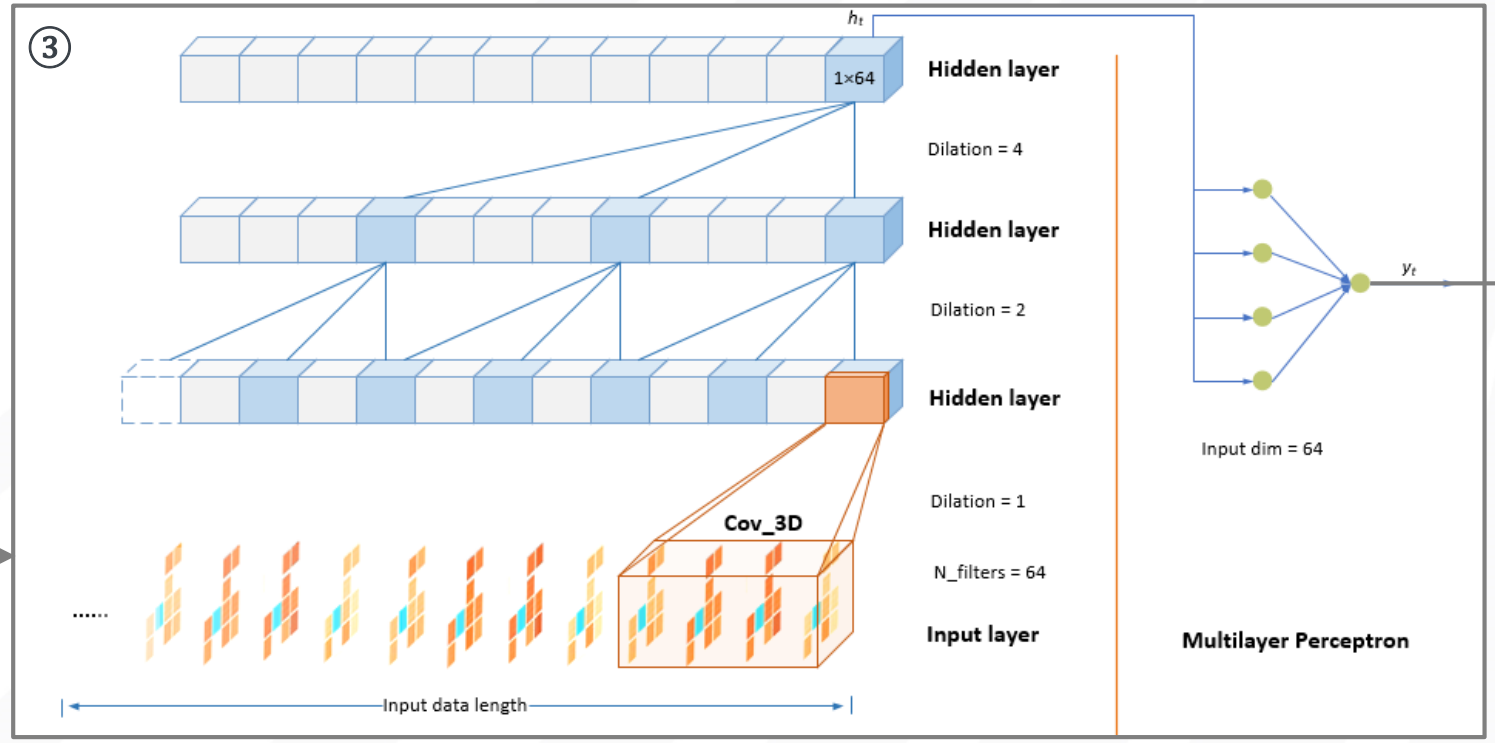
100 PV sites in NC state from strata solar



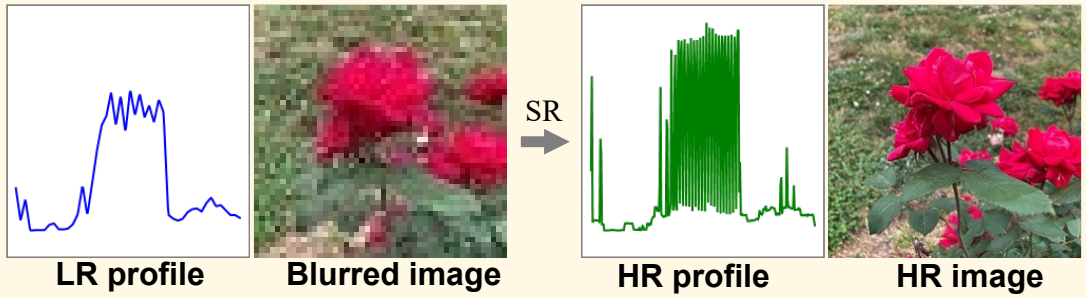
Spatial-temporal forecasting method in real-time stage

Yiyan Li, Lidong Song, Si Zhang, Laura Kraus, Taylor Adcox, Roger Willardson, Abhishek Komandur, and Ning Lu, "TCN-based Spatial-Temporal PV Forecasting Framework with Automated Detector Network Selection," https://arxiv.org/abs/2111.08809. submitted to IEEE Trans. Sustainable Energy.

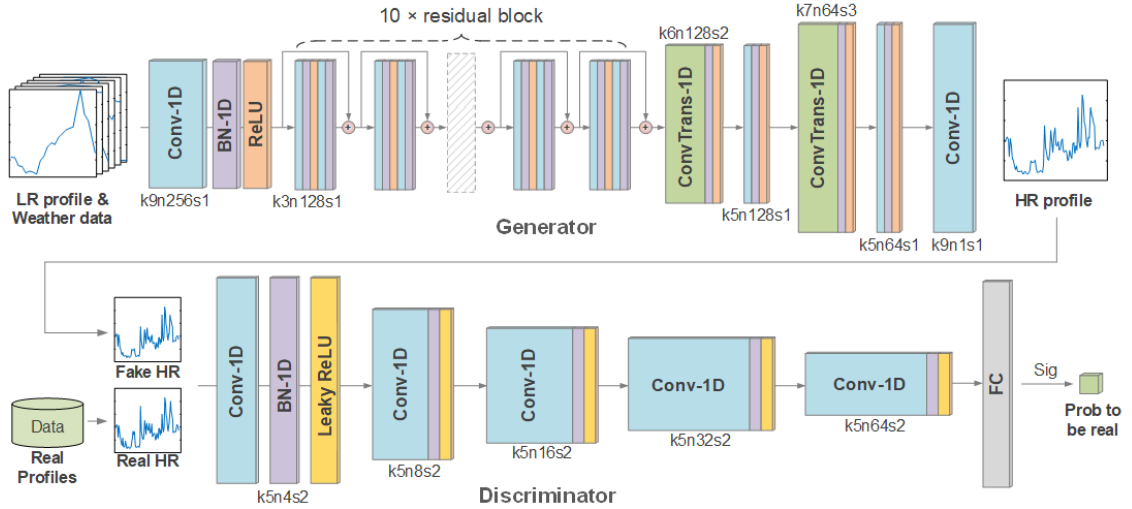
Situational Awareness (3): Load Profile Super-resolution (SR)

Develop high-resolution PV and load profiles

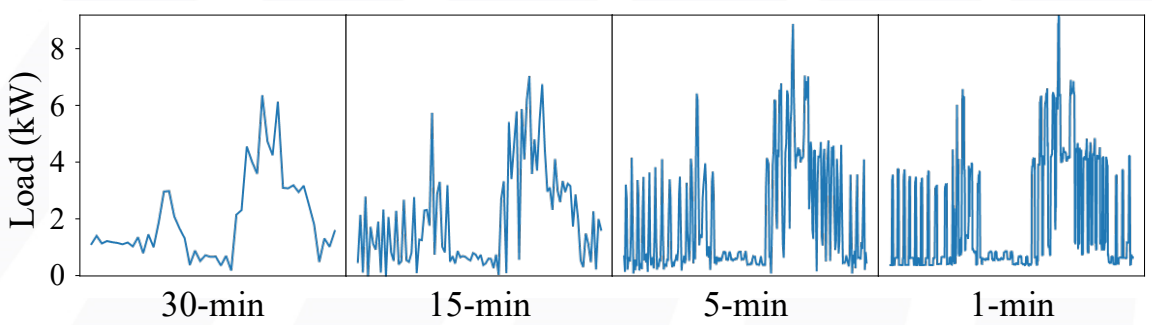
- Measurements uploaded from smart meter are usually averaged to **15-min** or **30-min** low resolution (LR)
- High-resolution (HR) load data is important in system situational awareness (e.g. peak load, load ramp)
- We restore the high-frequency load dynamics from the LR measurements using deep learning methods



A GAN-based Super-resolution Method



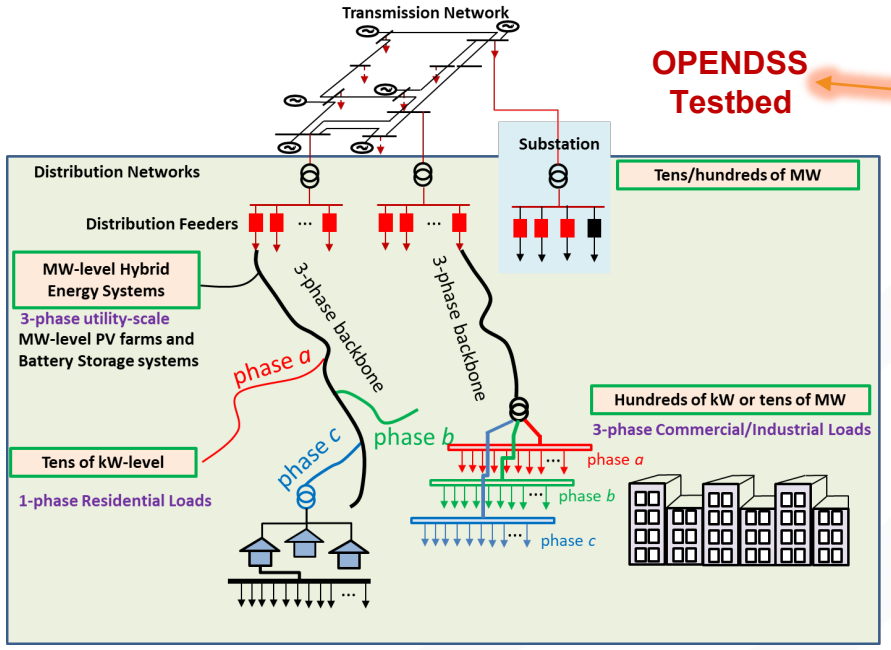
From 15-minutes → Minute-by-minute→ intra-minute



Lidong Song, Yiyan Li, and Ning Lu. "ProfileSR-GAN: A GAN based Super-Resolution Method for Generating High-Resolution Load Profiles." arXiv preprint arXiv:2107.09523 (2021). Submitted to IEEE Trans. Smart Grid, under 2st round review

PARS: A Nested, Highly-scalable Modeling Framework

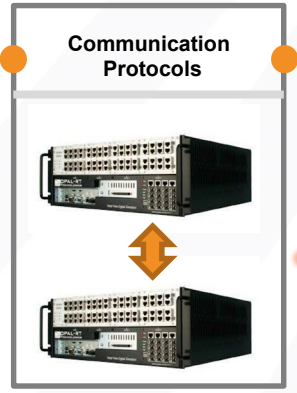
- **OPENDSS** for development and **OPAL-RT** testbed for testing
- **System-level:** Energy scheduling and power dispatch for managing uncertainties
- **Device-level:** Grid forming and grid following functions for dynamic responses



Simulation time frame:
- 24 Hour-ahead for every 30-minute time interval
- 30 minutes for every 5-minute time interval
- Faster-than-real-time, steady-state, optimal-response-actions

OPENDSS Testbed

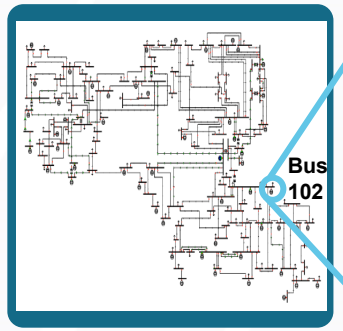
Model communication and cyber attacks



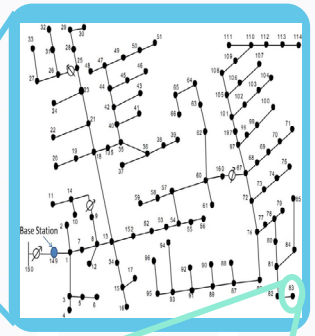
OPAL-RT Testbed

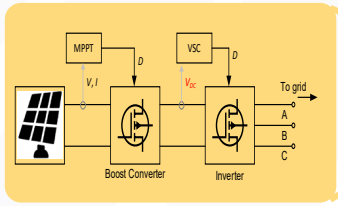
Simulation time frame:
- $\mu s \rightarrow ms$
- Slow and fast transients are modeled
- Operation limits → current, voltage, power
- Applications → protections and power quality

ms **Transmission IEEE 118 bus**



ms **Distribution IEEE 123 node**





PV systems

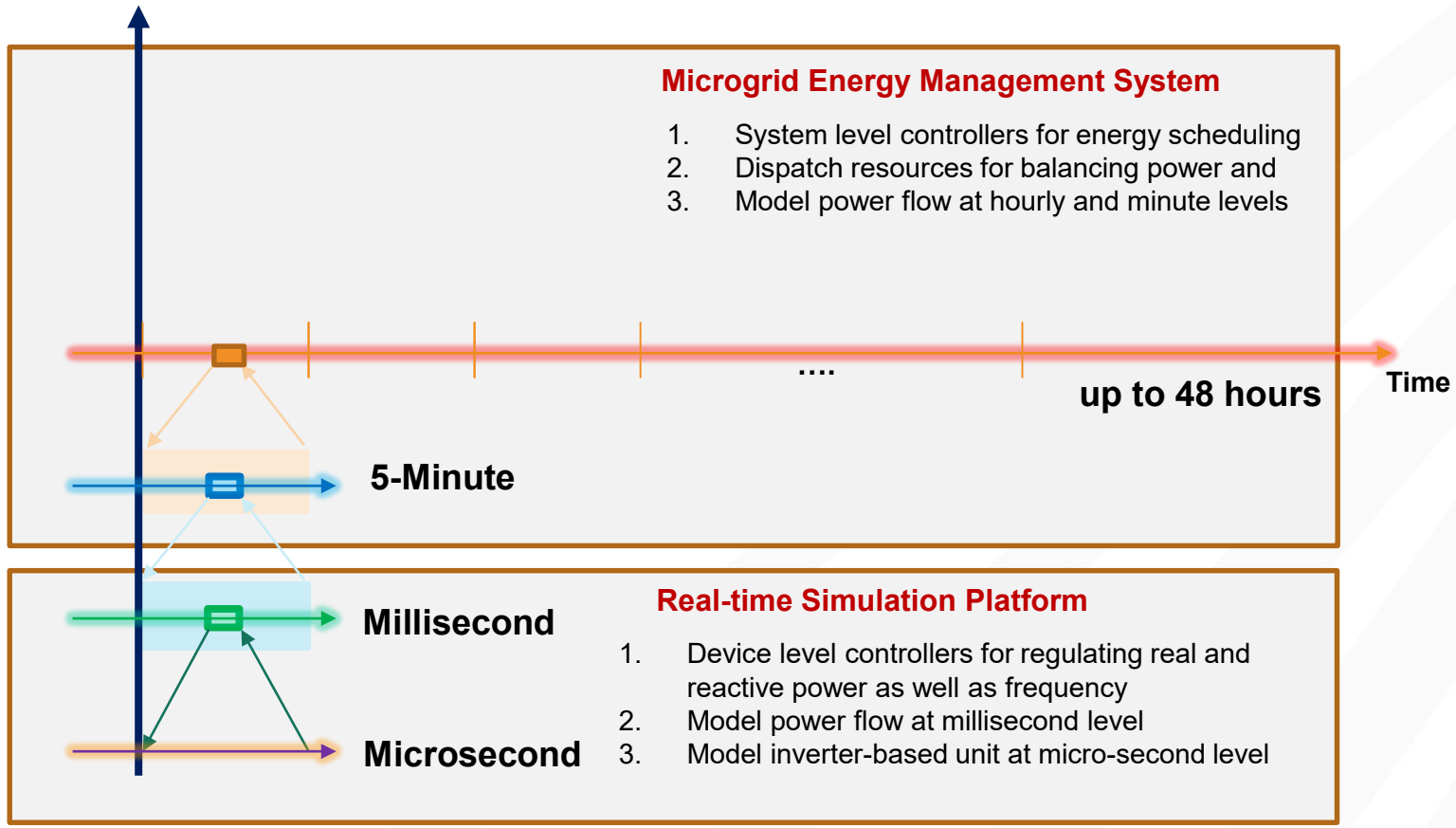
μs

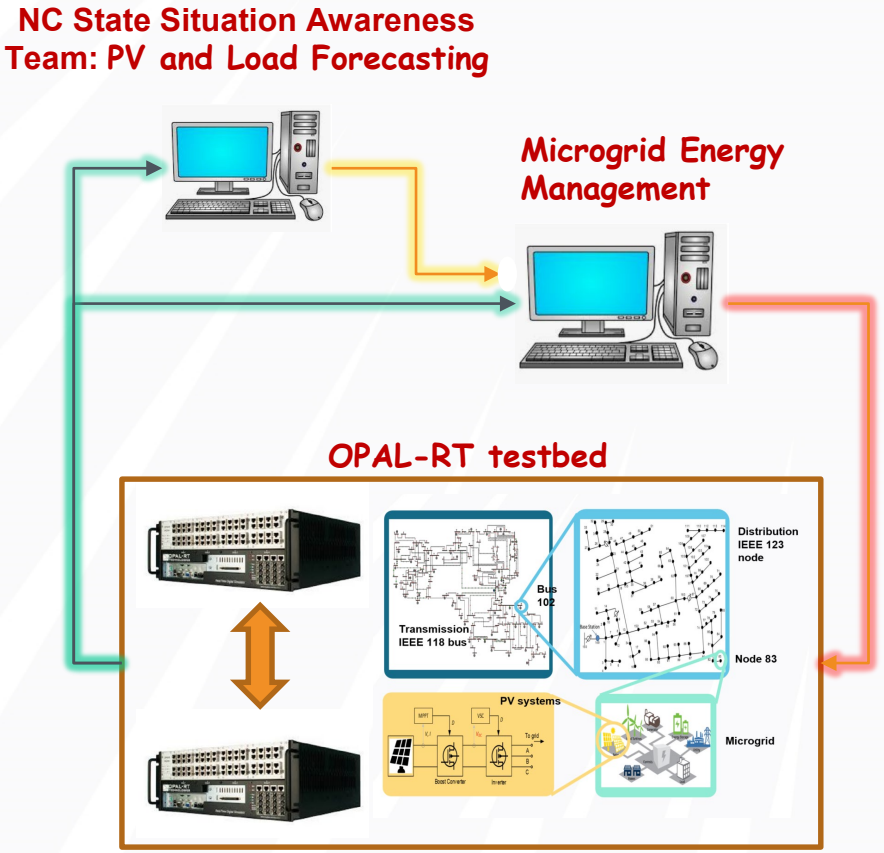
Microgrid

μs

Fuhong Xie, C. McEntee, M. Zhang, B. Mather and N. Lu, "Development of an Encoding Method on an Co-simulation Platform for Mitigating the Impact of Unreliable Communication," in *IEEE Transactions on Smart Grid*, Videos related with the paper: https://www.youtube.com/watch?v=SdibDKEpw60
F. Xie et al., "Networked HIL Simulation System for Modeling Large-scale Power Systems," 2020 52nd North American Power Symposium (NAPS).
F. Xie, C. McEntee, M. Zhang and N. Lu, "An Asynchronous Real-time Co-simulation Platform for Modeling Interaction between Microgrids and Power Distribution Systems," 2019 IEEE Power & Energy Society General Meeting (PESGM), Atlanta, GA, USA, 2019.

PARS: An **Asynchronous** Modeling Framework





Uniqueness of the PARS platform

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

Content

- An Overview of the PARS Project
- An Overview of the PARS Platform
- PARS PV-based Grid Support Function Development

NC State Modeling Team

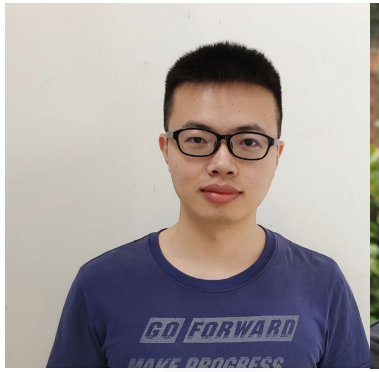
Project Lead by:

Dr. Ning Lu

Dr. Mesut Baran

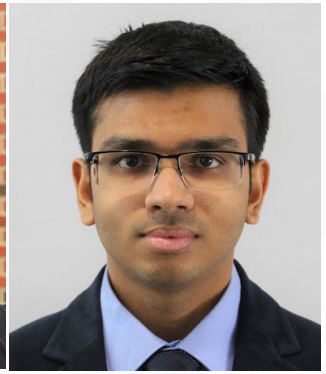
Dr. Wenyuan Tang

PhD Students:



Rongxing Hu

Valliappan Muthukaruppan



Ashwin Shirsat

Hyeonjin Kim

Graduated PhD Students:

Jiyu Wang

Catie McEntee

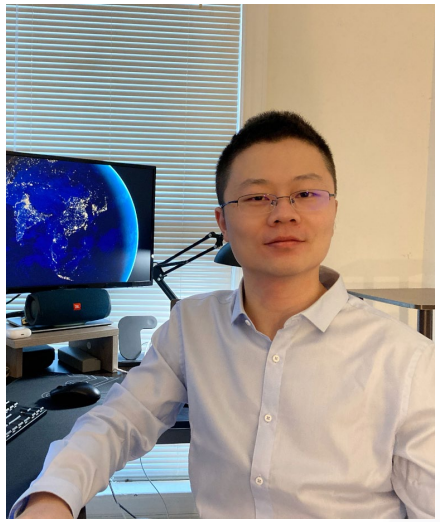
Asmaa Alrushoud

Ming liang

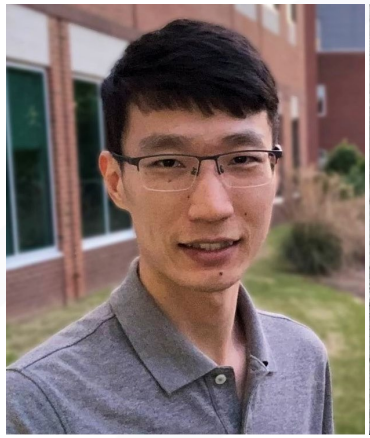
Situational Awareness Team

Project Lead by:

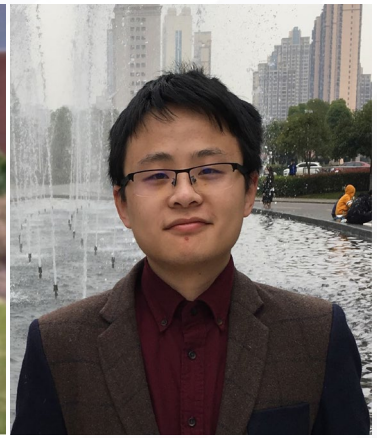
Dr. Yiyan Li



PhD Students:



Lidong Song



Si Zhang

Hanpyo Lee

Yi Hu

Kai Ye

Main Grid Support Functions Considered in T&D Restoration Operation

PARS-OMT

Transmission-HIL

1. Modeling NYPA Transmission network
2. Large-scale PV farms (100+ MW)
3. Large-scale Wind farms (100+ MW)
4. Bulk Energy Storage (tens of MW)
5. Composite Load Models

Distribution-HIL

1. Real distribution feeder topology and load data
2. Utility-scale MW-level PV
3. Community- and substation- level Energy Storage
4. Electric Vehicles Charging Stations
5. Composite Load Models for modeling load transients

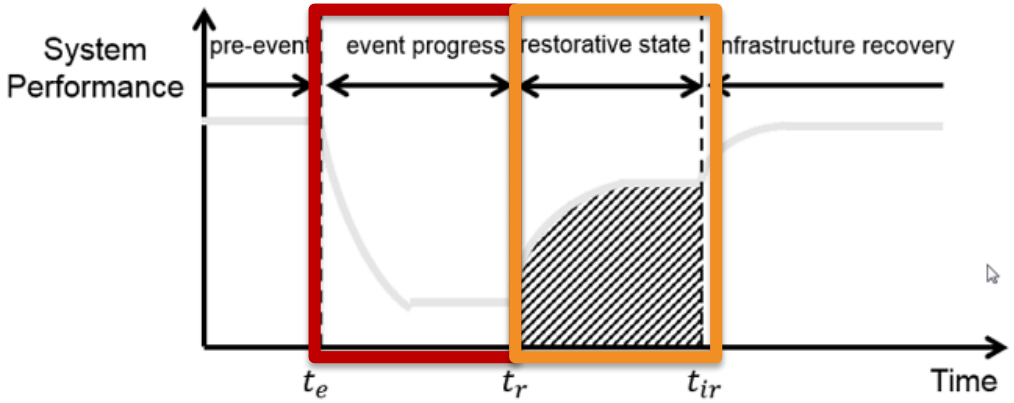
DER-HIL

1. BTM-PV
2. BTM-Energy Storage
3. BTM-Electric Vehicles
4. BTM-Controllable loads
5. BTM-Base Loads (ZIP loads, Motor loads, etc.)

OMT-Database

Type of hybrid PV systems		Typical Size	Pre-fault	During fault		Restoration		Normal Operation		
			Resiliency Services					Grid Services		
			Fault-ride through	Islanding	Microgrid Operation	Reconfiguration	Black-start	Cold-load-pickup	Real Power Regulation	Reactive Power Regulation	Frequency Regulation
BTM PV	Residential	1-20 kW	✓		X			X	✓	✓	✓
	Commercial	<1MW	✓	✓	✓	✓	✓	✓	✓	✓	✓
PV Farms	Distribution	1-50 MW	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Transmission	50+ MW	X	X		✓	✓		✓	✓	✓

Main goal: Develop new grid support functions that corresponding to the **4-stage of resiliency services**



Device-Level Grid-forming and Grid-following Functions

Plant-level Functions	Grid Support Functions	PV utility-scale	PV Roof-top	Energy Storage (Stationary/Mobile)	Diesel Generation	Loads
Grid-following	Real Power Regulation	✓	✓	✓	✓	
Grid-following	Reactive Power Regulation	✓	✓	✓	✓	
	Microgrid Formation	✓		✓	✓	
Grid-forming	Voltage and Frequency Regulation			✓	✓	
Grid-forming	**Manage 3-phase Load Unbalance**			✓	✓	
Grid-forming	Cold Load Pickup			✓	✓	✓
Grid-forming	Blackstart	✓		✓	✓	✓

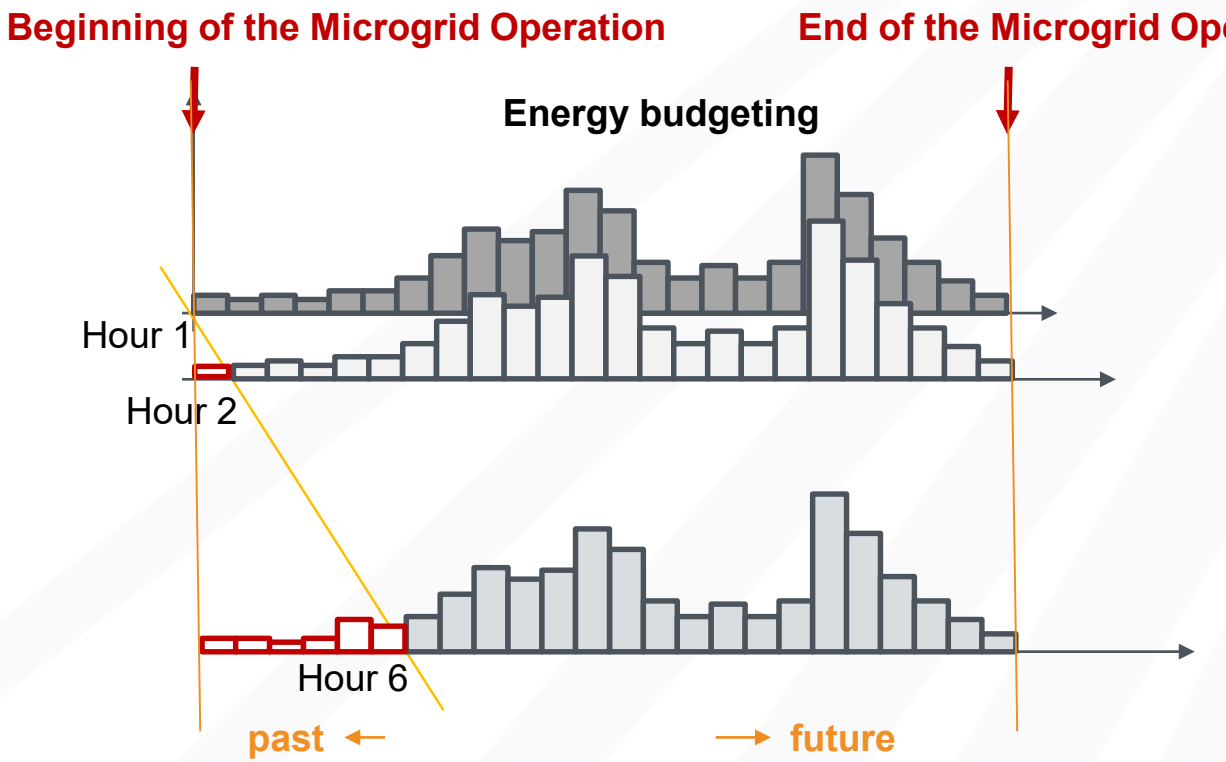
1. Victor Paduani, Huiyu Yu, Bei Xu, Ning Lu, "A Unified Power-Setpoint Tracking Algorithm for Utility-Scale PV Systems with Power Reserves and Fast Frequency Response Capabilities", https://arxiv.org/abs/2105.05324, accepted by the IEEE transactions on Sustainable Energy.
2. Victor Paduani, Lidong Song, Bei Xu, Dr. Ning Lu, "Maximum Power Reference Tracking Algorithm for Power Curtailment of Photovoltaic Systems", submitted to IEEE PES 2021 General Meeting. 2021. *arXiv preprint arXiv:2011.09555*.
3. 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," submitted to 2022 PES General meeting.

Managing Uncertainties 1: through Microgrid Energy Scheduling

- **"Energy Scheduling" is done for the entire microgrid operation period.**
- **Scheduling Interval: $\Delta t = 30$ minute or 60 minute**
- **Execute repetitively every Δt using the latest PV+load forecast**

Input

1. Forecasted PV and load
2. Initial SOC of the battery devices
3. Fuel storage for the diesel generators



Output

1. Battery charging and discharging schedule
2. Diesel generator generation schedule
3. Controllable loads
4. Reconfiguration schedules (breaker on/off)

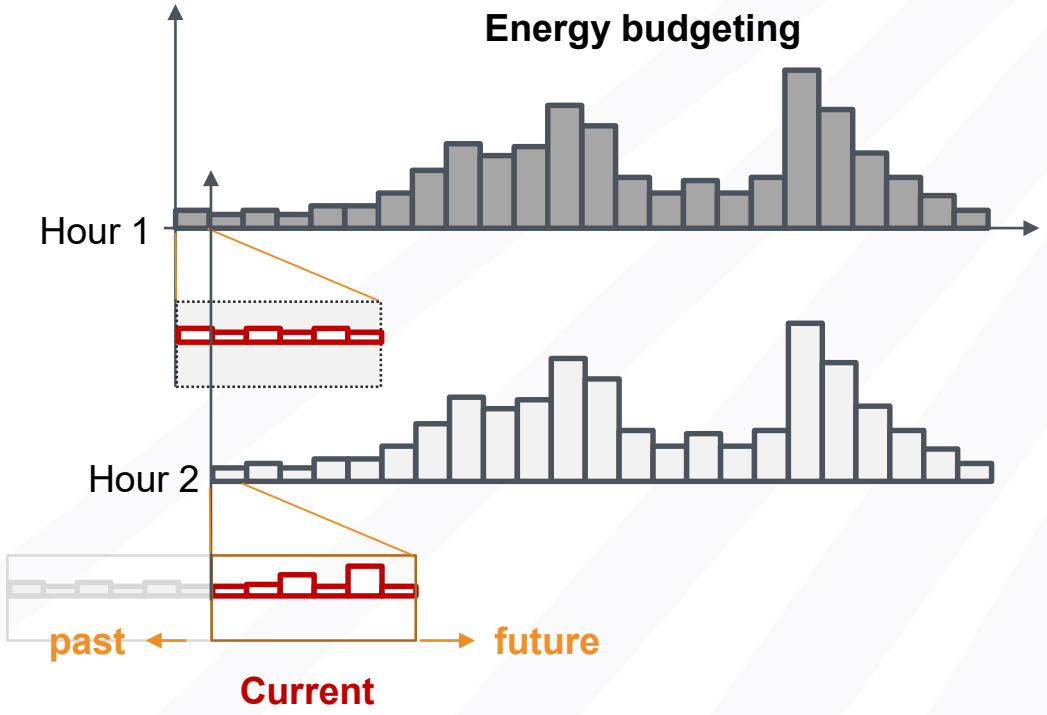
1. Rongxing Hu, Yiyan Li, Si zhang, Valliappan Muthukaruppan, Ashwin Shirsat, Mesut Baran, Wenyuan Tang, David Lubkeman, Ning Lu, "A Load Switching Group based Feeder-level Microgrid Energy Management Algorithm for Service Restoration in Power Distribution System", submitted to IEEE PES 2021 General Meeting. 2021. Available online at:https://arxiv.org/abs/2011.08735
2. Ashwin Shirsat, Valliappan Muthukaruppan, Rongxing Hu, Ning Lu, Mesut Baran, David Lubkeman, Wenyuan Tang, "Hierarchical Multi-timescale Framework for Operation of Dynamic Community Microgrid", submitted to IEEE PES 2021 General Meeting. 2021. https://arxiv.org/abs/2011.10087

Managing Uncertainties 2: through Load Following and Power Balancing

- **"Energy Scheduling" is done for each scheduling period Δt (30~60 minutes)**
- **Scheduling Interval: $\Delta\tau = 5$ minute**
- **Can execute repetitively every $\Delta\tau$ using the real-time PV+load forecast**

Input

1. Forecasted PV and load
2. Initial SOC of the battery devices
3. Fuel storage for the diesel generators



Output

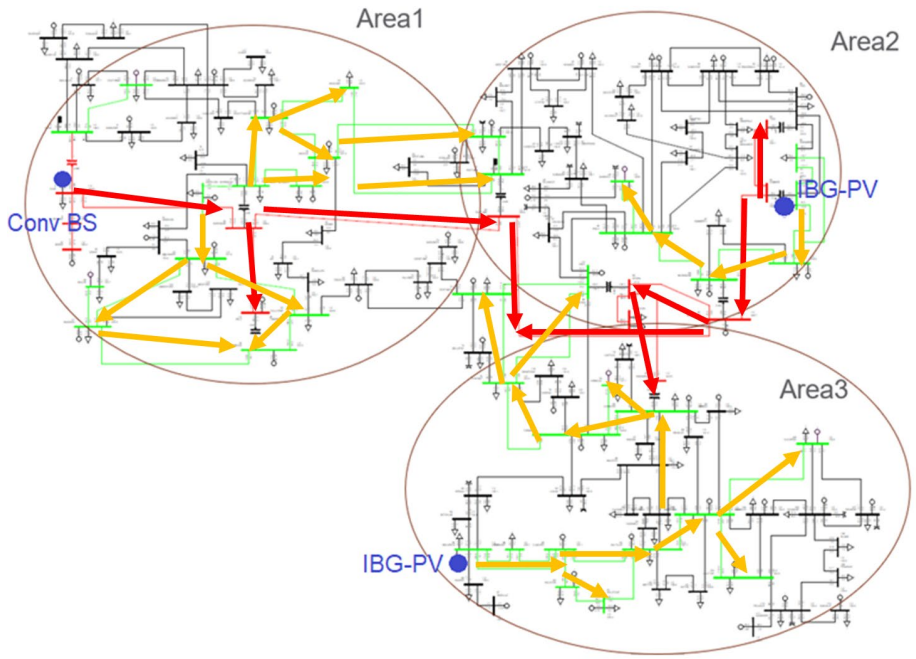
1. Battery charging and discharging schedule
2. Diesel generator generation schedule
3. **Controllable loads**
4. Reconfiguration schedules (breaker on/off)

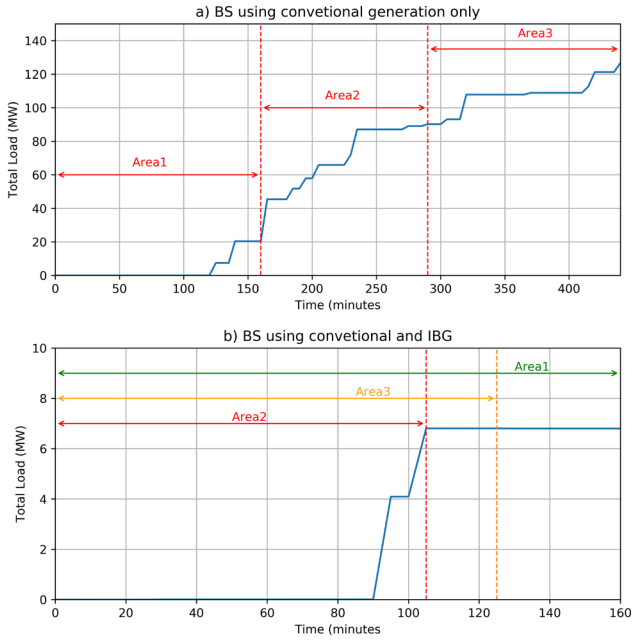
1. Rongxing Hu, Yiyan Li, Si zhang, Valliappan Muthukaruppan, Ashwin Shirsat, Mesut Baran, Wenyuan Tang, David Lubkeman, Ning Lu, "A Load Switching Group based Feeder-level Microgrid Energy Management Algorithm for Service Restoration in Power Distribution System", submitted to IEEE PES 2021 General Meeting. 2021. Available online at:https://arxiv.org/abs/2011.08735
2. Ashwin Shirsat, Valliappan Muthukaruppan, Rongxing Hu, Ning Lu, Mesut Baran, David Lubkeman, Wenyuan Tang, "Hierarchical Multi-timescale Framework for Operation of Dynamic Community Microgrid", submitted to IEEE PES 2021 General Meeting. 2021. https://arxiv.org/abs/2011.10087

Blackstart Sequence Modeling Using IEEE 118-bus System

Utilizing IBG significantly reduces

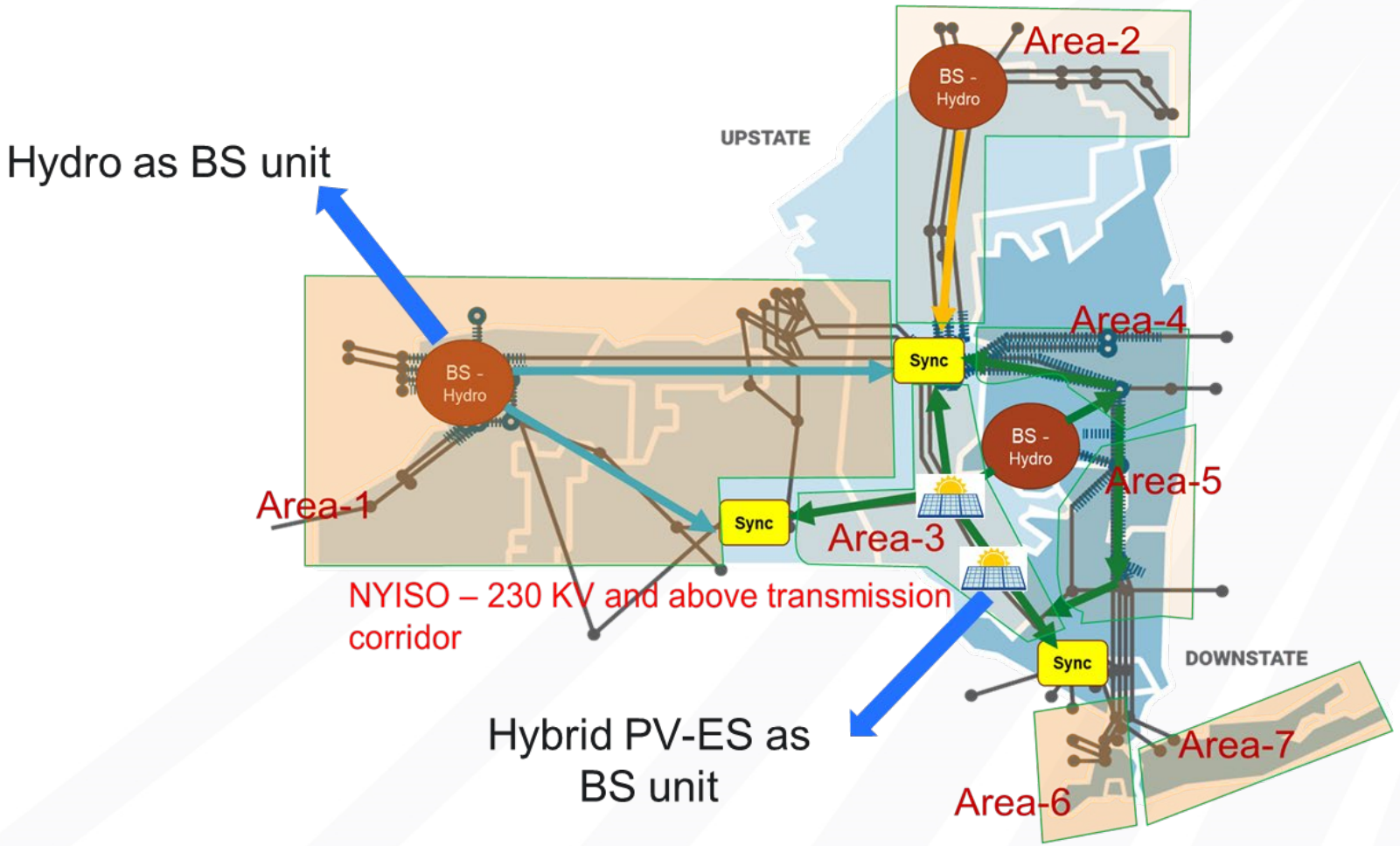
- The time to energize transmission backbone (1/3 of the time)
- The amount of dispatchable load (factor of 18)





1. Nguyen, Quan, Jim Ogle, Xiaoyuan Fan, Xinda Ke, Mallikarjuna R. Vallem, Nader Samaan, and Ning Lu. "EMS and DMS Integration of the Coordinative Real-time Sub-Transmission Volt-Var Control Tool under High DER Penetration." *arXiv preprint arXiv:2103.10511* (2021).
2. Nguyen, Q., Vallem, M.R., Vyakaranam, B., Tbaileh, A., Ke, X. and Samaan, N., 2021. Control and Simulation of a Grid-Forming Inverter for Hybrid PV-Battery Plants in Power System Black Start. *arXiv preprint arXiv:2103.11239*.
3. Tbaileh A., M.R. Vallem, Q.H. Nguyen, X. Ke, N.A. Samaan, G. Stefopoulos, and X. Jiang. "Optimal Power System Black start using Inverter-Based Generation." In IEEE PES GM 2021.

Blackstart Sequence Modeling using NYPA Network Model

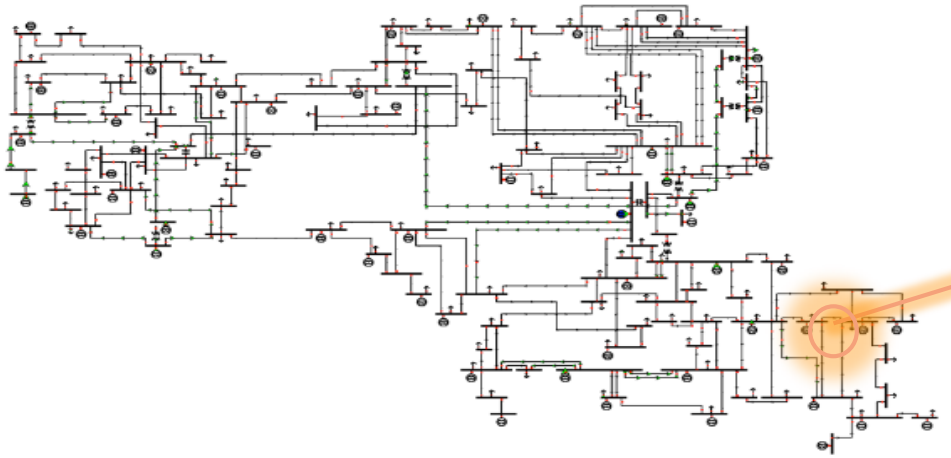


[NY Poised to Make Largest Grid Investment in 30 Years - NYISO]

Distribution Level - 3 Use Cases

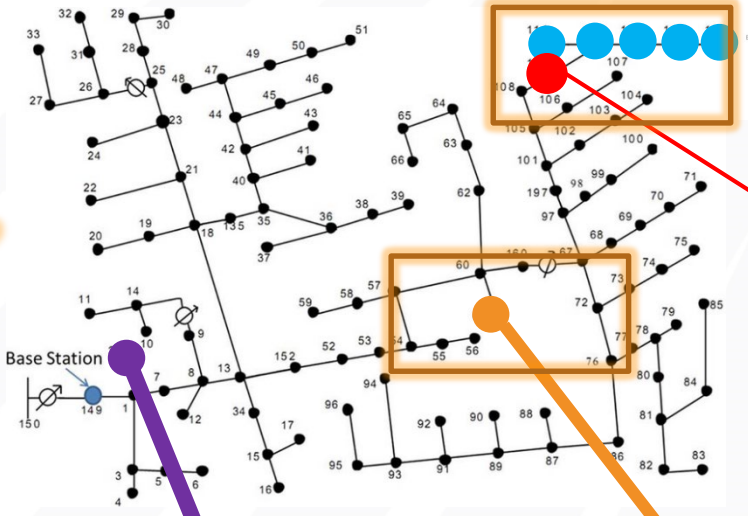
Pacific Northwest National LAB

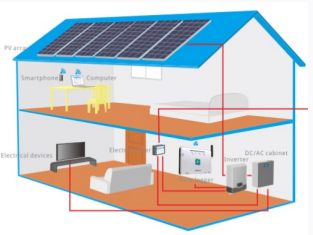
Transmission power grid



NC State at Raleigh, NC

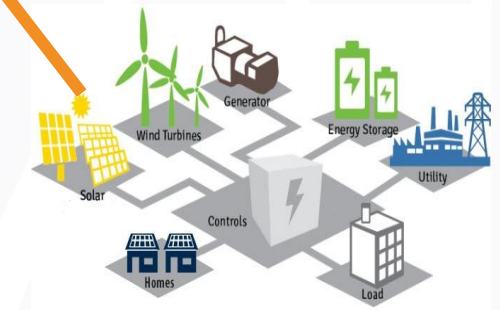
Distribution power grid





Mobile Storage enhanced Small PV systems

PV-powered feeder-level Microgrid



Community Microgrid

Industry advisors:

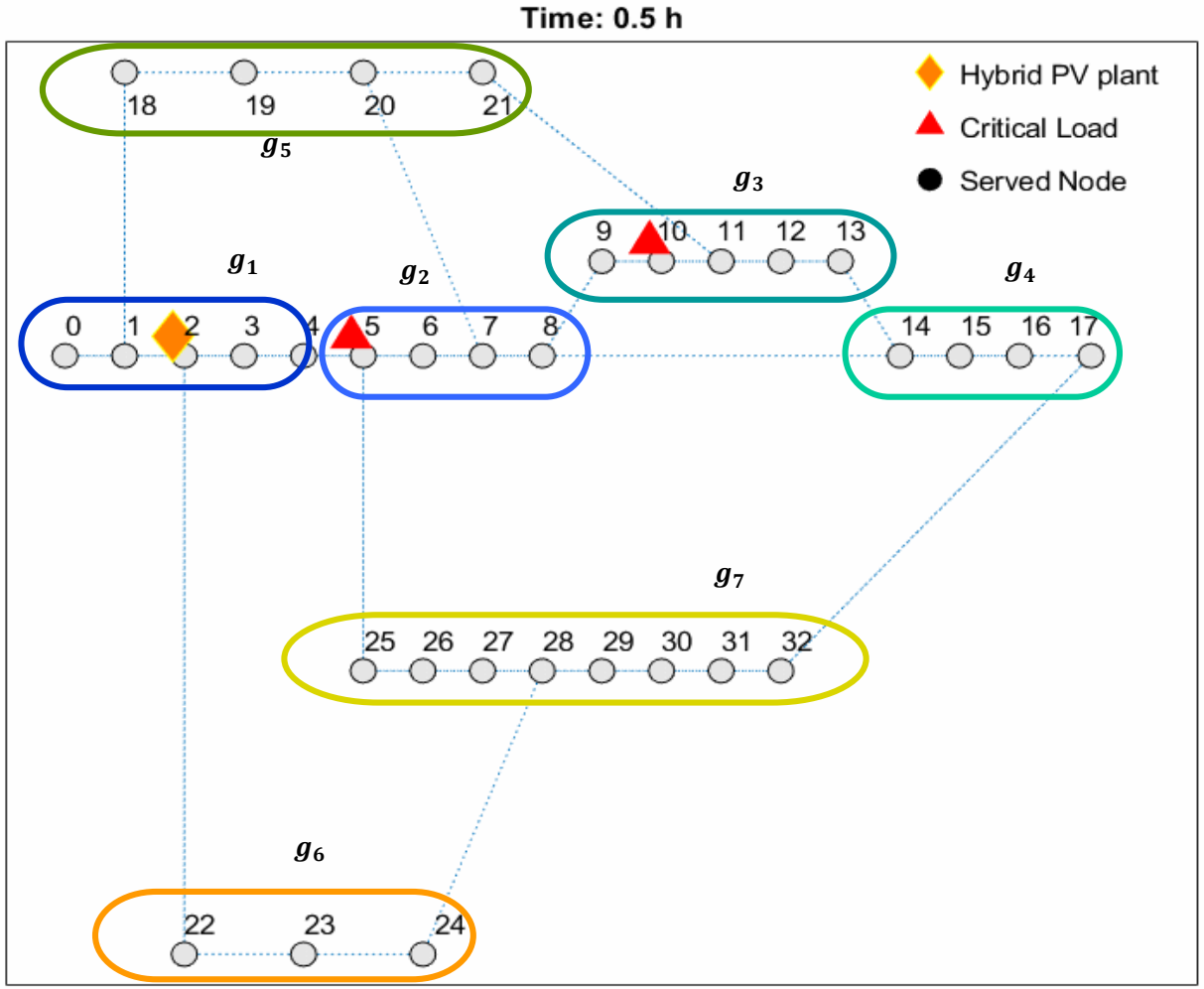
1. Strata Solar
2. ElectriCities
3. Wison Energy/New Rivers
4. Roanoke ElectricCooperative

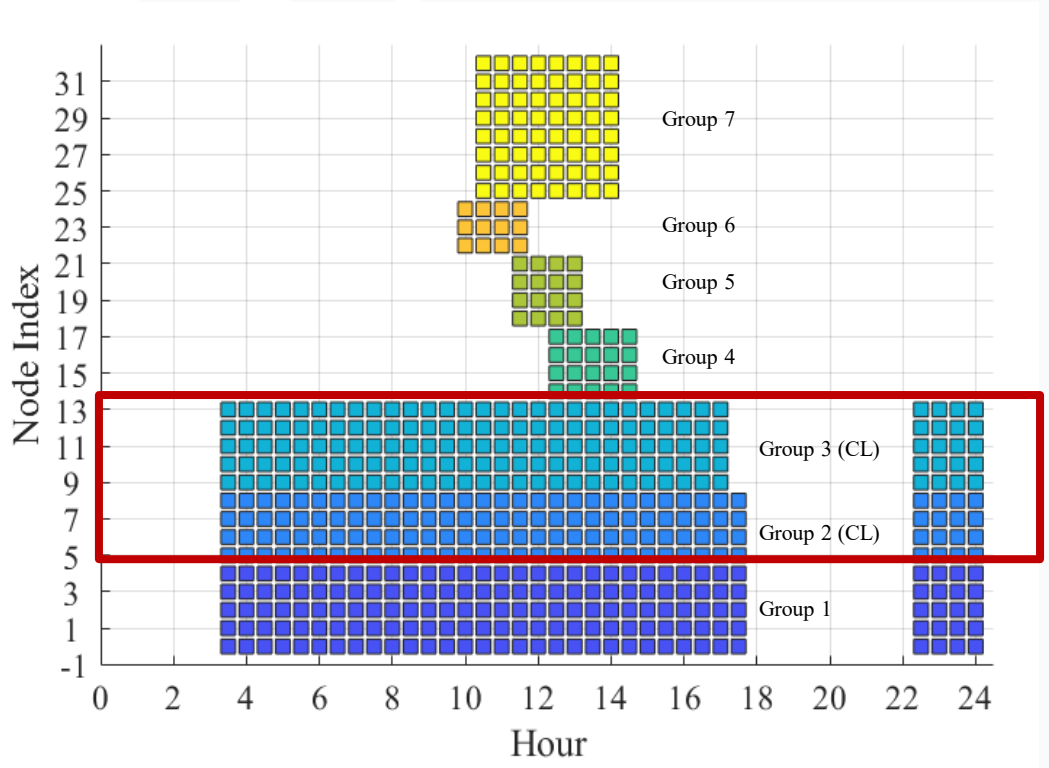
Controllable Distributed Energy Resources

	Reconfiguration	PV	Battery	Diesel Generator	Load	Cold Load Pickup	Phase Load Balance
MW-level PV farms	All sectionalizers are controllable	Fully observable and controllable	MW-level fully controllable	None	Control load in the 2nd stage	Considered	Considered
Residential kW-level PV	All sectionalizers are controllable	Rooftop PV not controllable and observable	Installed at the feeder-head fully controllable and are used	Yes	No load control	Considered	Not Considered
Community PV with hundreds of kW	Can control adjacent sectionalizers	Community PV observable and controllable. Residential rooftop PV not observable	Co-located as a part of microgrid and with one or two customers	Yes	Control load in 2nd stage via demand response	Considered	Considered

1. **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", submitted to IEEE PES 2021 General Meeting. 2021. Available online at:https://arxiv.org/abs/2011.08735
2. **Ashwin Shirsat,** Valliappan Muthukaruppan, Rongxing Hu, Ning Lu, Mesut Baran, David Lubkeman, Wenyuan Tang, "Hierarchical Multi-timescale Framework for Operation of Dynamic Community Microgrid", submitted to IEEE PES 2021 General Meeting. 2021. https://arxiv.org/abs/2011.10087

An Example of Energy Management Results





- The service range of the microgrid changes fast around midday
- Group 2 receives a longer service than group 3

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", submitted to IEEE PES 2021 General Meeting. 2021. Available online at:https://arxiv.org/abs/2011.08735

Content

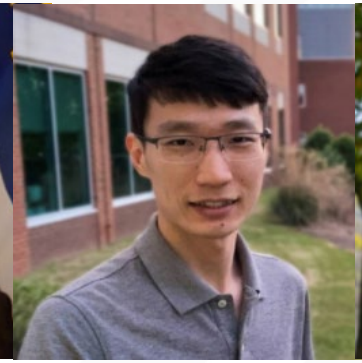
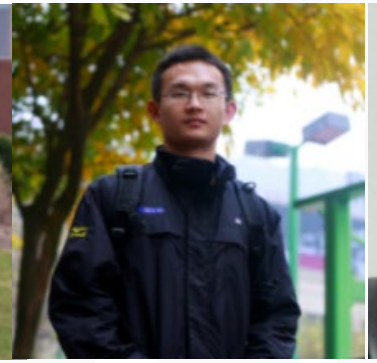
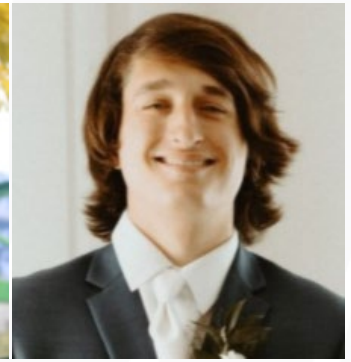
- An Overview of the PARS Project
- An Overview of the PARS Platform
- PARS PV-based Grid Support Function Development
- **Real-time Simulation Test System Development**

NC State HIL Team

This work is lead by:
Dr. David Lubkeman
Dr. Srdjan Lukic

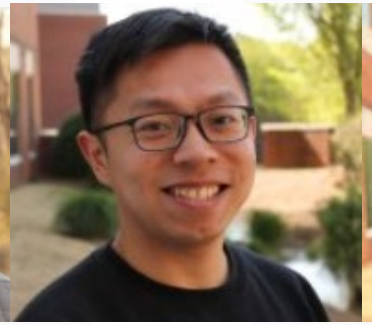
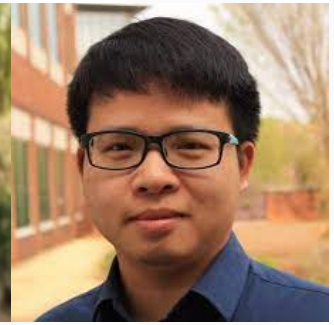

PhD students:



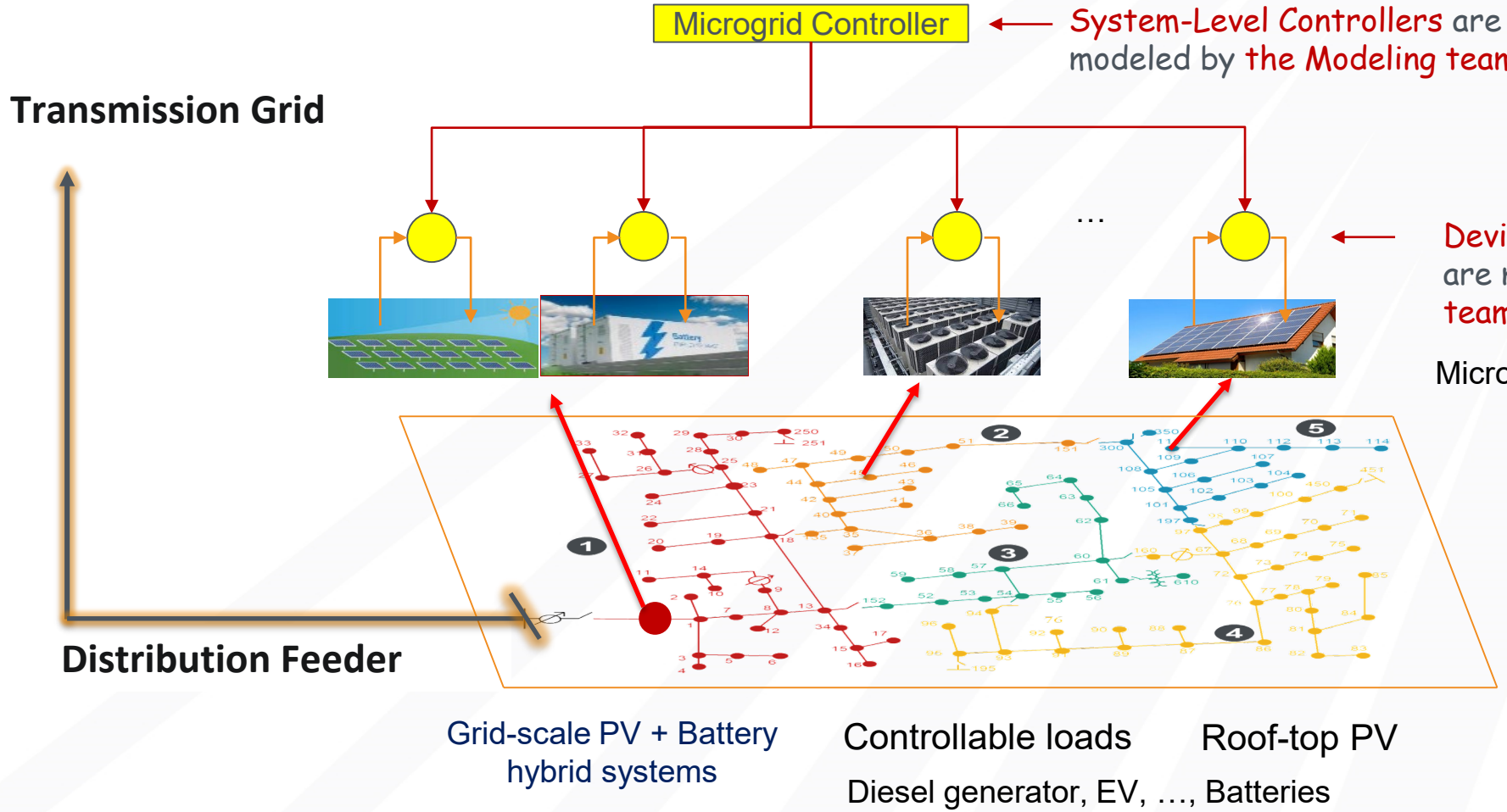
Victor Paduani **Bei Xu** **Lidong Song** **Qi Xiao** **Charles Kelly**

Graduated
PhD students:

Fuhong Xie **Long Qian** **Hui Yu**

Coordination: System-Level Control Versus Device-level Control



1.Mingzhi Zhang, Xiangqi Zhu, and Ning Lu. "A Data-driven Probabilistic-based Flexibility Region Estimation Method for Aggregated Distributed Energy Resources", submitted to IEEE Transaction on Sustainable Energy. 2021. https://arxiv.org/abs/2110.07406.

Use-cases Implementation Progress

- **Features of the HIL platform:**
  - **Real-time**
  - Realistic **communication**
  - **Device-level** controllers and sensors
  - **System-level: external microgrid controllers**

- **Testing Procedures:**
  - -Validate stability in Simulink
  - -Implement model for HIL tests
  - -Insert unintentional communication errors
  - -Insert intentional errors (cyber attacks)

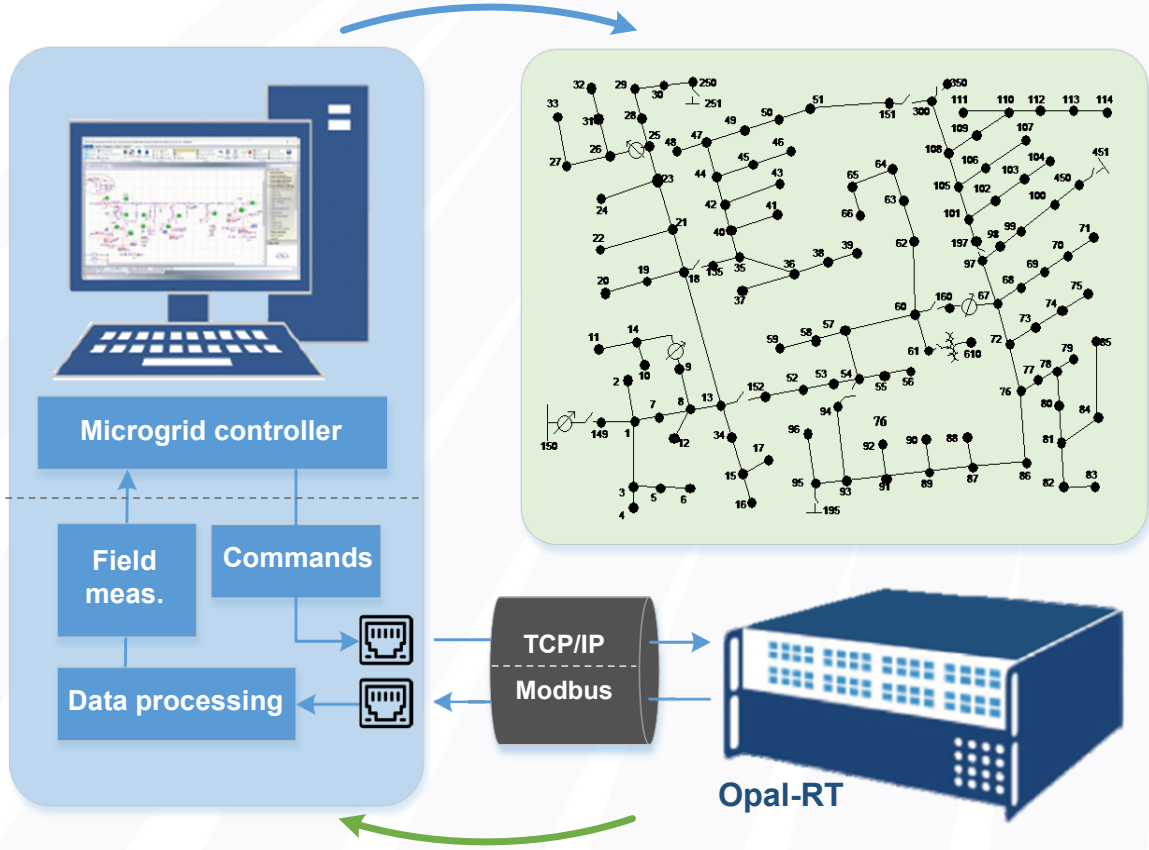
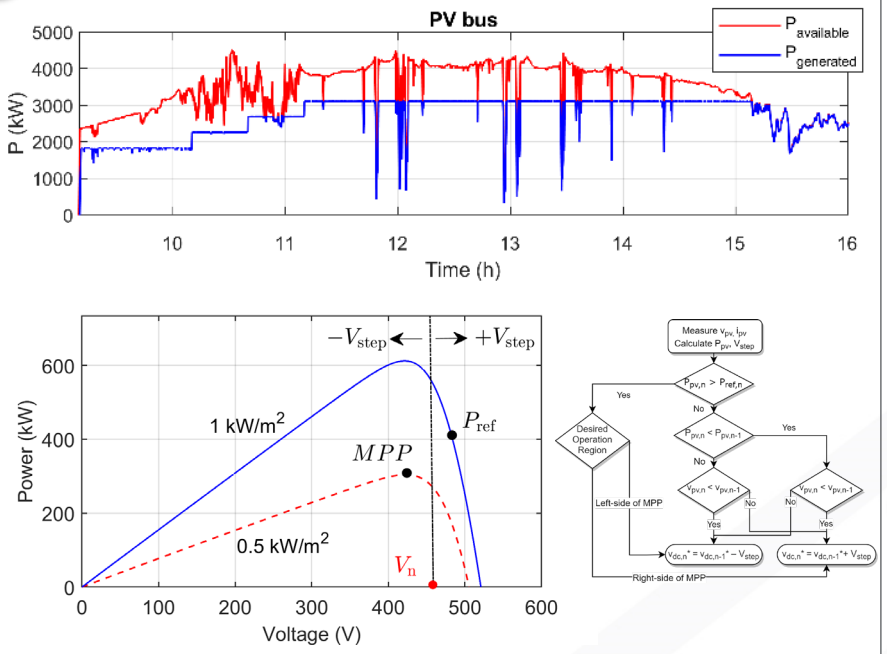


Diagram of HIL platform

Restoration Scenario	Simulink	Day-long HIL	Unreliable communication	Cyber attacks
Utility-Scale PV	✓	✓	ongoing	ongoing
Rooftop PV	✓	✓	ongoing	ongoing
Dynamic Microgrids	✓	✓	ongoing	ongoing

Real-time Simulation: PV Plant – Main functionalities in detail

1

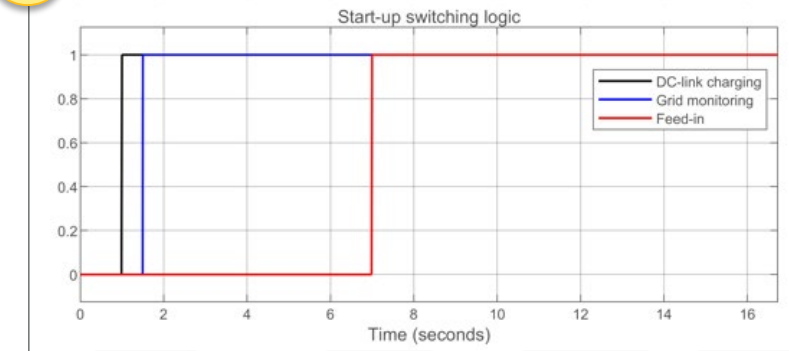


- Setpoint tracking under irradiance intermittency
- Allows PV to provide power reserves

Fast response power curtailment algorithm [1]

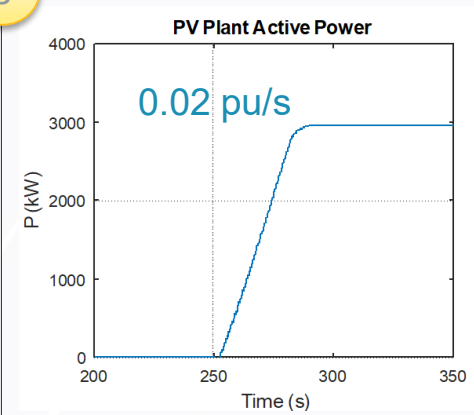
[1] Paduani, Victor, et al. "Maximum Power Reference Tracking Algorithm for Power Curtailment of Photovoltaic Systems." *In Proceedings PESGM 2021*

2



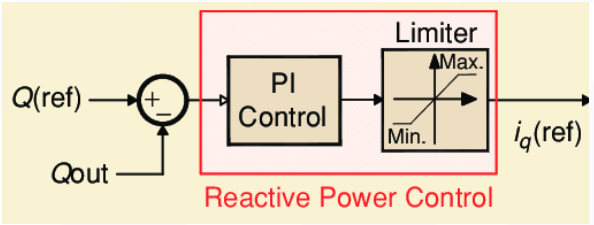
Start-up switching logic

3



Ramping capability

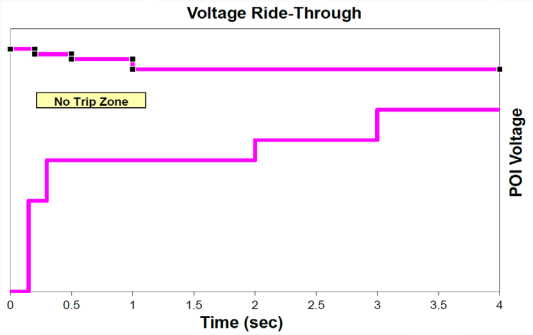
4



- Voltage schedule
- Power factor control

Reactive power control modes

5

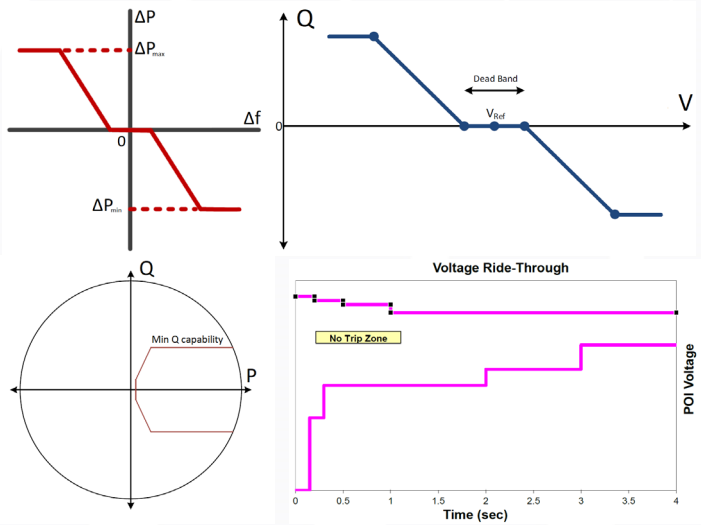


Disturbance ride-through

Rooftop PV system – Grid-following Functions

Module	Functionality	Requirement
Rooftop PV	**Active power curtailment**	Can follow power curtailment setpoints.
	Disturbance ride-through	Trips in accordance with default settings from IEEE 1547-2018
	Reactive power control modes	Provides all reactive power control modes established for Category II-B DER from IEEE 1547-2018.
	Frequency-watt droop	Provides f-watt droop to support the grid.
	Voltage-active power droop	Can curtail their output power if the grid voltage increases (optional mode)
	Code-based model	Implemented in a code-based environment to provide an alternative model without block diagrams (reducing model)

Includes IEEE 1547-2018 Category II-B DER requirements:



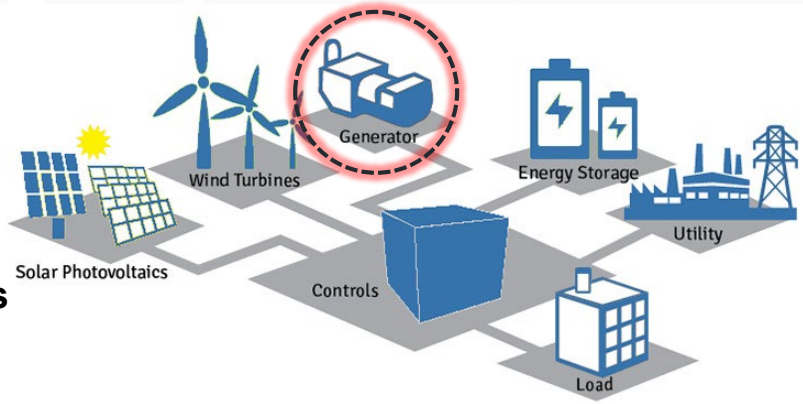
- **Main differences** of Rooftop PV model compared to PV Plant:
  - -Runs in **phasor domain** (no waveforms)
  - -**larger time-step**
  - -**No DC-link dynamics**
  - -Different **Q-ctrl** modes
  - -**Lower computational cost (can model 100's of units)**

Paduani, Victor, et al. "Maximum Power Reference Tracking Algorithm for Power Curtailment of Photovoltaic Systems." *In Proceedings PESGM 2021*

Diesel Generator – Model developed to date

Module	Functionality	Requirement
Diesel Generator	Ramping Capability	Can regulate its output power ramping to a prespecified p.u./s for improving system robustness.
	Grid Synchronization	Can adjust its voltage magnitude and phase for a smooth grid synchronization.
	Fuel Consumption Estimation	Calculates the fuel consumption.
	Mode switching capability – grid forming / grid-following	Can operate in grid-forming or grid-following modes.
	Power factor control	Can follow active power setpoint and a given power factor.
	Disturbance ride-through	Will trip in accordance with PRC-024-2 (NERC)

Diesel Generator (DG)



Structure of a low-inertia microgrid

Study the interactions between the synchronous generator and the inverter based resources

- Functionalities are developed to give the modeling team full control over the DG's output p
- Can be used to evaluate how a DG can **assist a low-inertia microgrid** in the future.
- Provides backup energy for moments of low solar/BESS availability.
- Design utilizes synchronous machine model from [1].

[1] *"Simplified synchronous machine. Mathworks R2006a."*

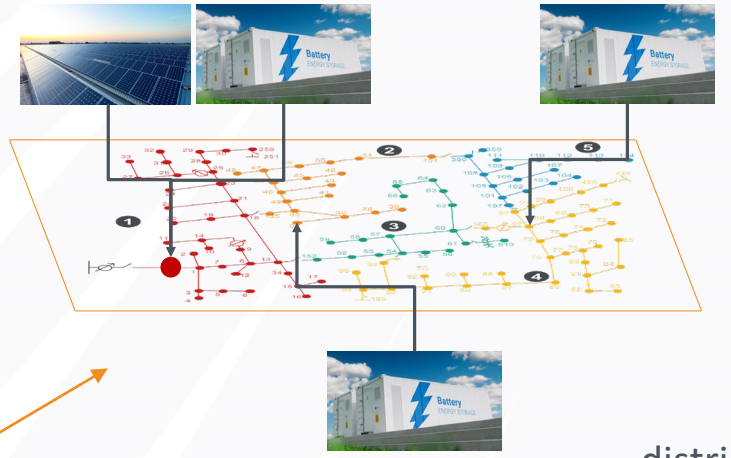
Q. Long, H. Yu, F. Xie, N. Lu and D. Lubkeman, "Diesel Generator Model Parameterization for Microgrid Simulation Using Hybrid Box-Constrained Levenberg-Marquardt Algorithm," in *IEEE Transactions on Smart Grid*, doi: 10.1109/TSG.2020.3026617.

BESS – Model developed to date

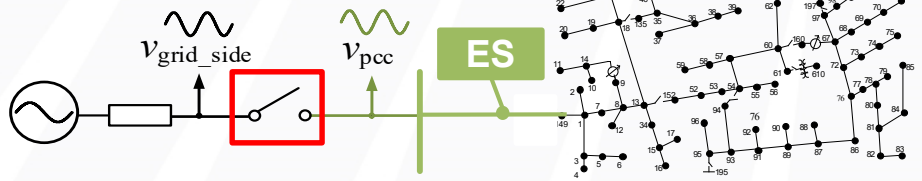
Module	Operation mode	Functionality	Requirement
Battery Energy Storage Model (**BESS**)	**Grid-forming** mode	Voltage and frequency regulation	It's responsible for regulating PCC voltage and setting the system frequency.
		Three-phase **imbalance** control	If the distribution grid is imbalanced, ES should 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	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.

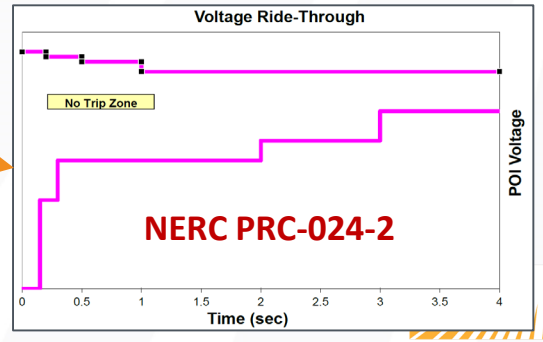
One battery storage unit

Multiple battery storage units



distribution grid

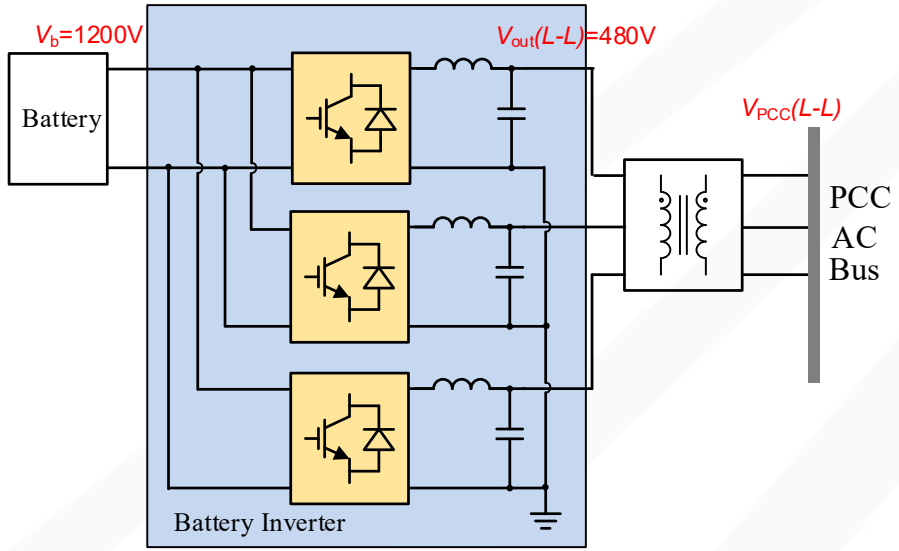




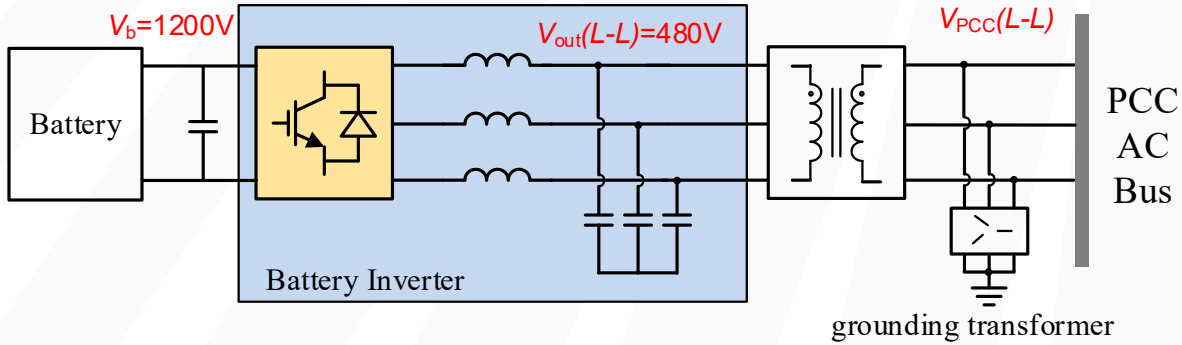
Bei Xu, Victor Paduani, David Lubkeman, and Ning Lu, "A Novel Grid-forming Voltage Control Strategy for Supplying Unbalanced Microgrid Loads Using Inverter-based Resources," submitted to 2022 PES General meeting.

BESS – Model developed to date

	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: $\|P_a\|$, $\|P_b\|$, $\|P_c\| \le P_{rated}$	BESS power limitation for unbalance regulation: 1) power unbalance factor* ≤ 0.6; 2) $\|P_a\|$, $\|P_b\|$, $\|P_c\| \le 0.95\ P_{rated}$
Grid-following mode	Output power for each phase is controllable.	Output power can't be controlled per phase



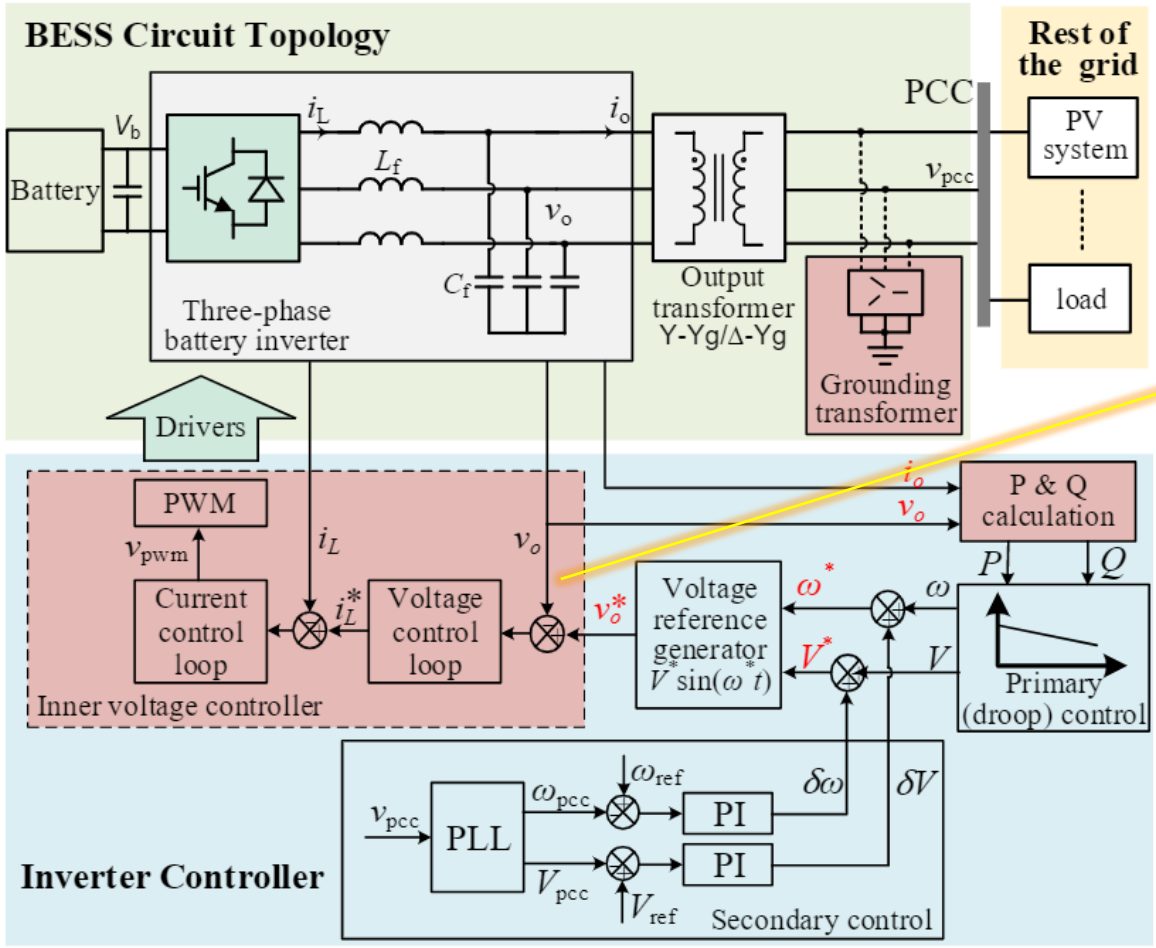
Three Single-phase Inverter Model



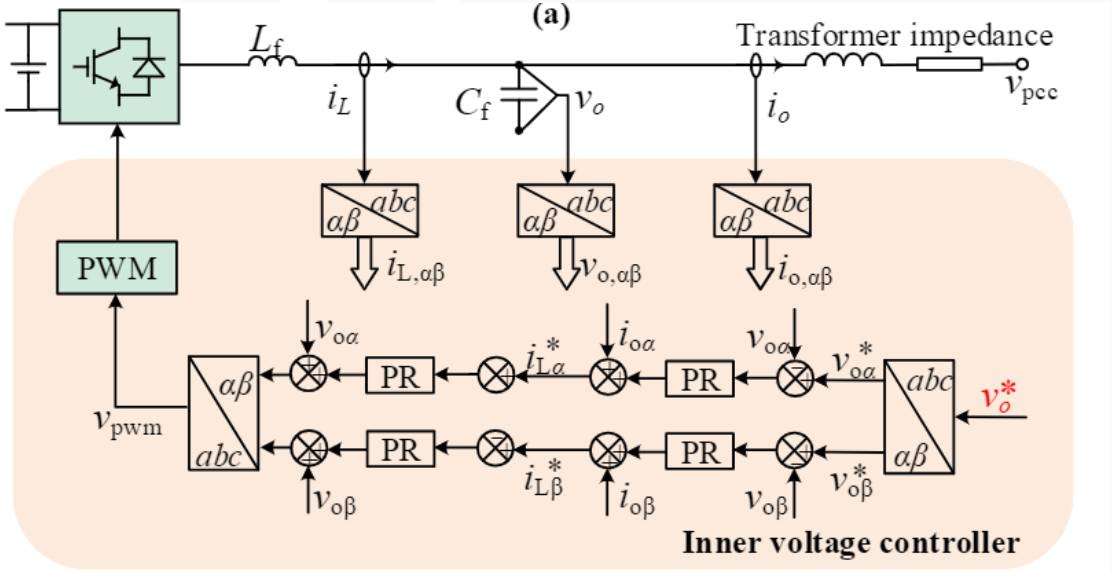
Three-phase Inverter Model

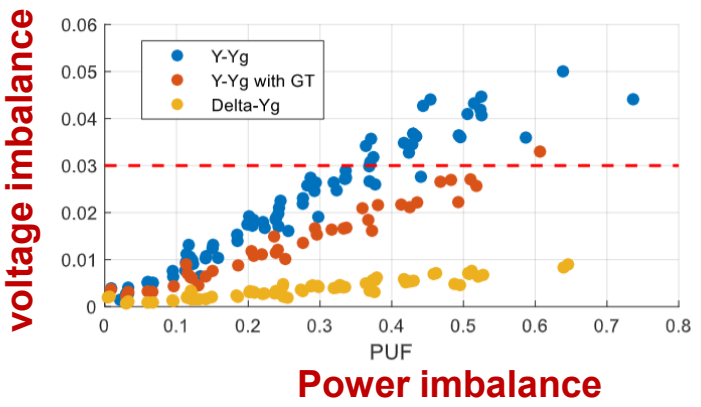
Bei Xu, Victor Paduani, David Lubkeman, and Ning Lu, "A Novel Grid-forming Voltage Control Strategy for Supplying Unbalanced Microgrid Loads Using Inverter-based Resources," submitted to 2022 PES General meeting.

BESS: Topology and Control of a 3-phase Grid-forming Inverter



$\alpha\beta$ stationary reference frame (SRF)

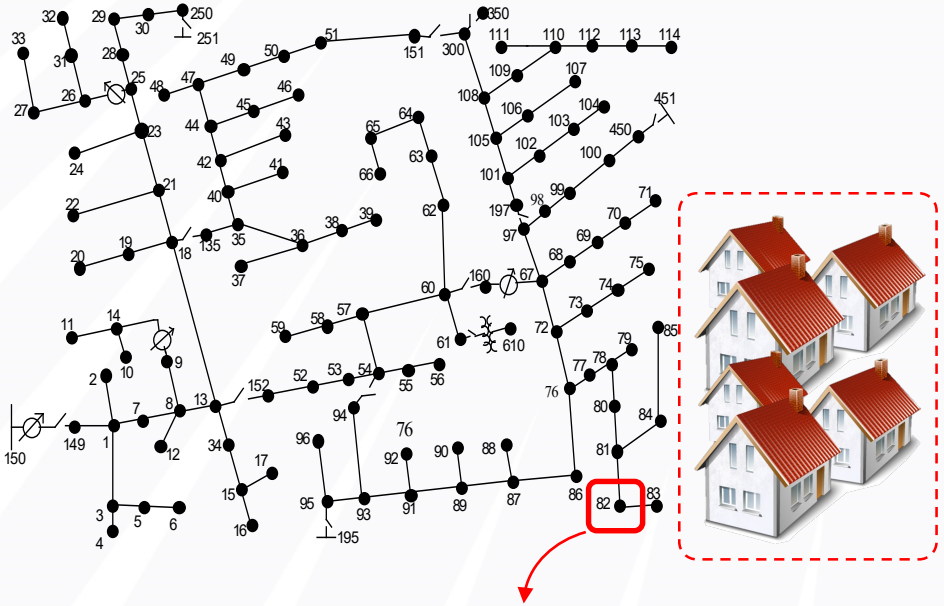


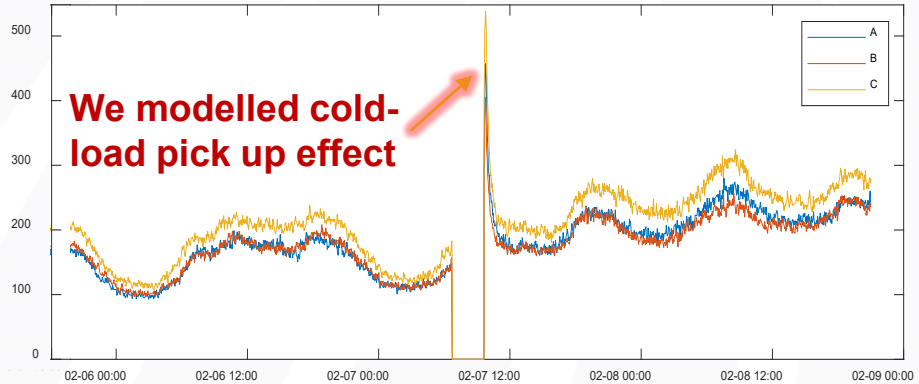


Bei Xu, **Victor Paduani, David Lubkeman, and Ning Lu, "A Novel Grid-forming Voltage Control Strategy for Supplying Unbalanced Microgrid Loads Using Inverter-based Resources," submitted to 2022 PES General meeting.**

Load – Model developed to date

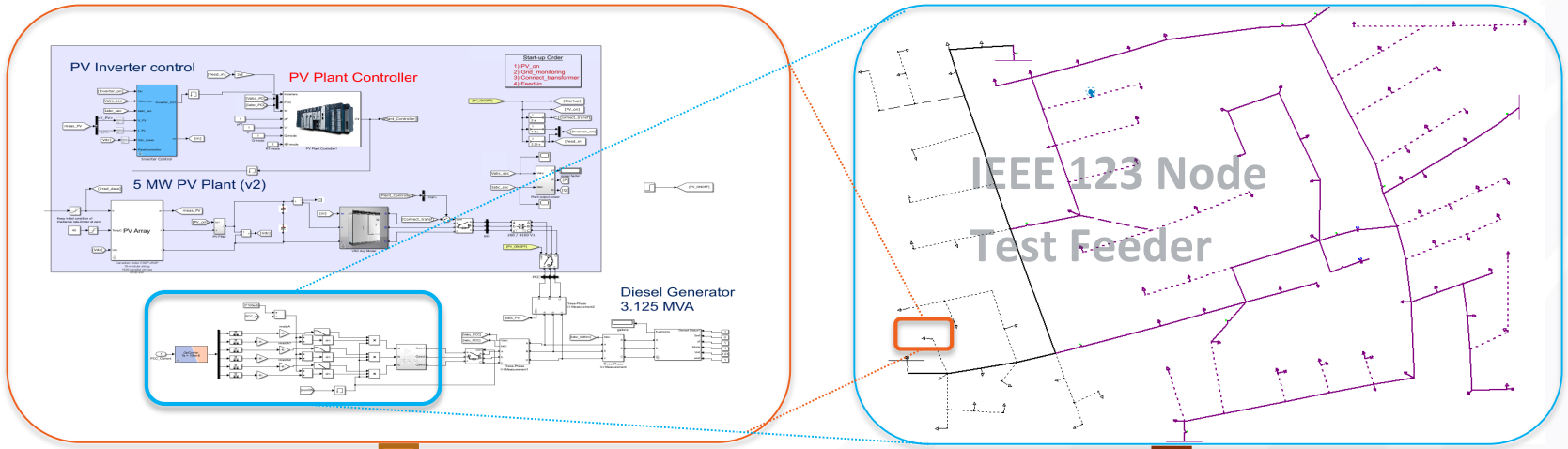
	Functionality	Requirement
Load Model	**Realistic load profile** synthesis	• Generate node load profile from smart meter data actual load data. • Use Super–Resolution algorithms for increased data resolution
	Modeling demand response (pay-back and cold load effects): **HVAC load modeling**	Model the behavior of HVAC load regarding house scale and appliance parameters
	Load model **parameterization**	Estimate the parameters of the state-space model based on actual HVAC load profile
	Real-time **Cold Load Pickup** (CLPU) profile generation	Generate real-time cold-load-pickup response according to the commands from EMS system

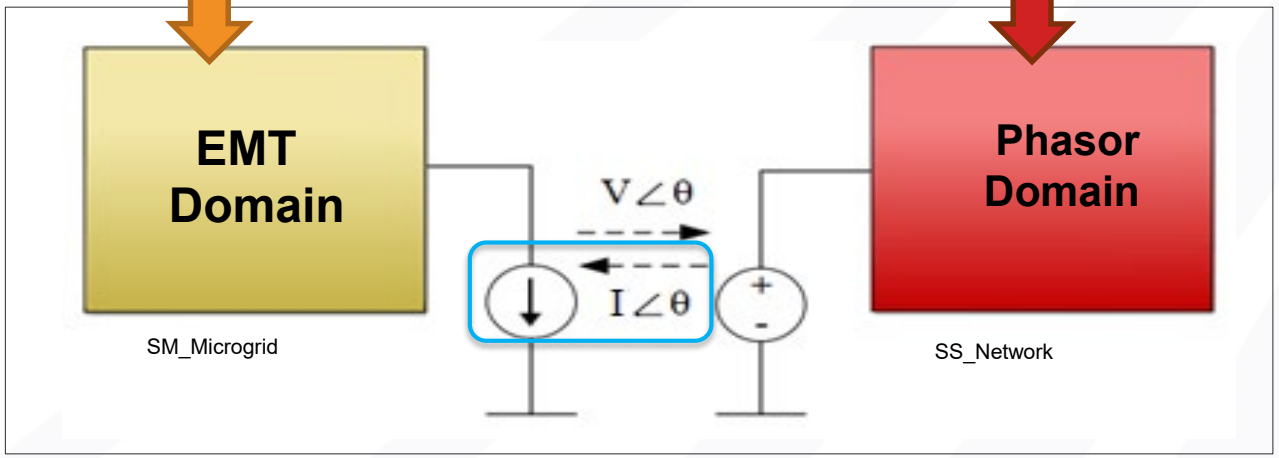




Lidong Song, Yiyan Li, and Ning Lu. "ProfileSR-GAN: A GAN based Super-Resolution Method for Generating High-Resolution Load Profiles." arXiv preprint arXiv:2107.09523 (2021). Submitted to IEEE Trans. Smart Grid, under 2st round review

EMT-Phasor Co-simulation – Performance Benchmarking

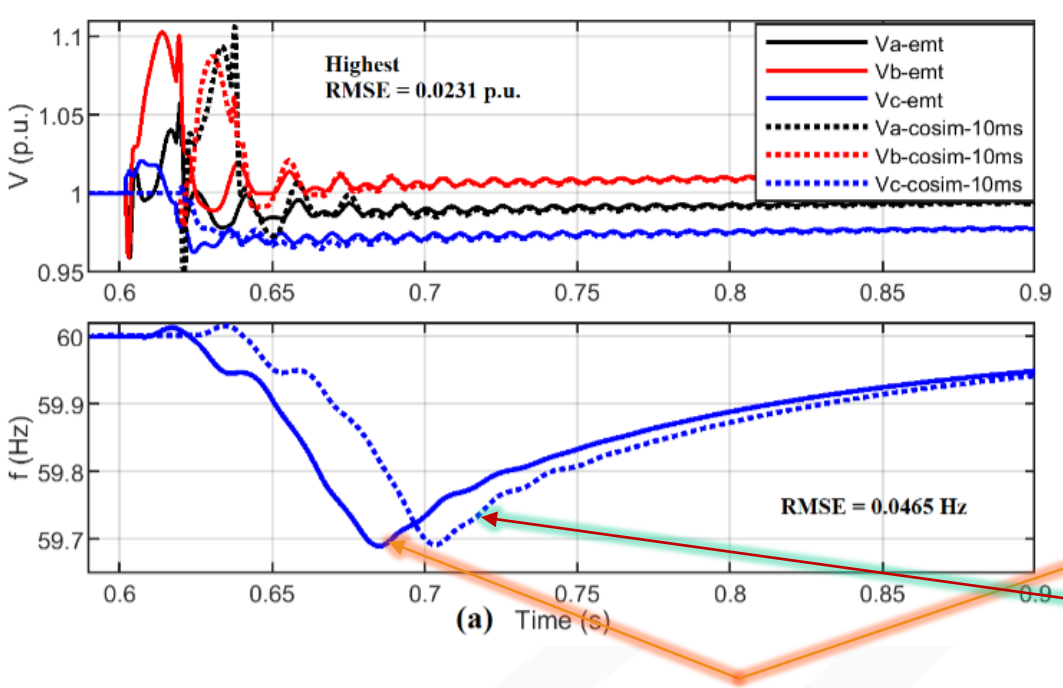


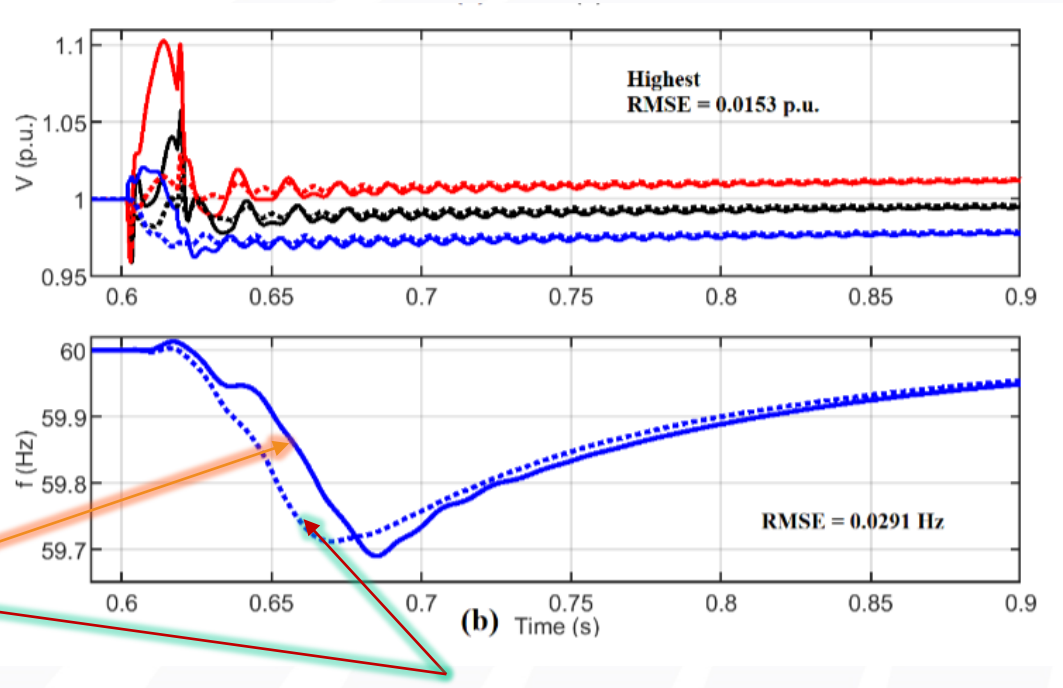


- **Use full EMT models** for benchmarking the EMT-Phasor co-simulation test systems and access the **boundary conditions**
- **Determine the operation limits for the** co-simulation to be effective (hold our required simulation accuracy)

[1] Xie, Fuhong, et al. "An asynchronous real-time co-simulation platform for modeling interaction between microgrids and power distribution systems." *2019 IEEE PESGM*.
[2] Victor Paduani, Bei Xu, David Lubkeman, Ning Lu, "Novel Real-Time EMT-TS Modeling Architecture for Feeder Blackstart Simulations," submitted to *2022 IEEE PESGM*.

Impact of Communication Delays and data interpolation for Coupling





EMT

(a) increasing the communication delay between EMT and phasordomains;

EMT-Phasor Cosimulation

(b) utilizing the time interpolation coupling technique

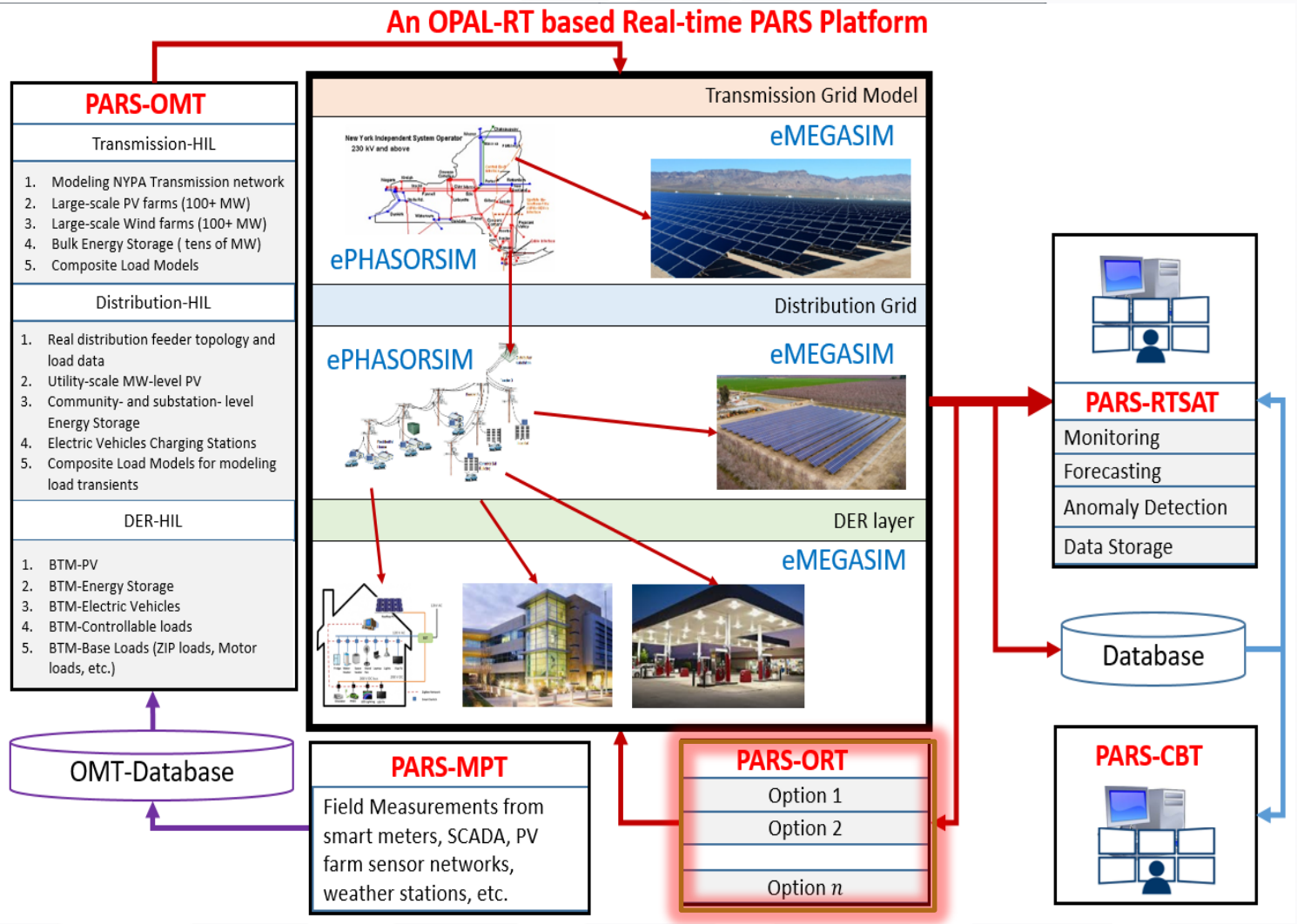
Victor Paduani, Bei Xu, David Lubkeman, Ning Lu, "Novel Real-Time EMT-TS Modeling Architecture for Feeder Blackstart Simulations," submitted to *2022 IEEE PESGM*.

Content

- An Overview of the PARS Project
- An Overview of the PARS Platform
- PARS PV-based Grid Support Function Development
- Real-time Simulation Test System Development
- Optimal Response Tool Development

Faster-than Real-time for Optimal Response Option Selection

Case	Outage Duration (h)	Computational Time (In seconds)			
		Stage 1	Stage 2	Stage 3	Sum
1 MW PV	24	426	178	X	**604**
	48	1269	350	X	**1619**
2 Mobile Storage	24	3633	294	X	**3927**
	48	5426	535	X	**5961**
3 Community Microgrid	24	1023	620	425	**2068**
	48	1387	1976	844	**4207**



Conclusion

- The PARS approach is summarized as follows:
  - Develop grid support functions using faster-than-real-time tools
  - Test and validate performance on real-time simulation platforms with communication links
  - Coordination between system-level and device-level controllers
  - Incorporate forecasting into energy and power management and consider device-level dynamic responses between power management intervals
- High-fidelity Digital Twins are important for developing new grid support functions
  - Compared with field tests, testing on digital twins are safer, cheaper, faster, and scalable
  - 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; ….
- Machine learning applications can help
  - Meta-learning for forecasting, GAN-based model for load profile generation, reinforcement learning for demand response control, …

List of Publications

Full Author List	Article Title	Journal/Conference
Li, Yiyan, Si Zhang, Rongxing Hu, and Ning Lu	A Meta-learning based Distribution System Load Forecasting Model Selection Framework	Applied Energy
F. Xie, C. McEntee, M. Zhang, B. Mather and N. Lu,	Development of an Encoding Method on an Co-simulation Platform for Mitigating the Impact of Unreliable Communication	IEEE transactions on smart grid
Q. Long, H. Yu, F. Xie, N. Lu and D. Lubkeman	Diesel Generator Model Parameterization for Microgrid Simulation Using Hybrid Box-Constrained Levenberg-Marquardt Algorithm	IEEE Transactions on Smart Grid
M. Liang, Y. Meng, J. Wang, D. Lubkeman and N. Lu,	FeederGAN: Synthetic Feeder Generation via Deep Graph Adversarial Nets	IEEE Transactions on Smart Grid
H. Yu, M. A. Awal, H. Tu, I. Husain and S. Lukic	Comparative Transient Stability Assessment of Droop and Dispatchable Virtual Oscillator Controlled Grid-Connected Inverters	IEEE Transactions on Power Electronics
Wang, Jiyu, Xiangqi Zhu, Ming Liang, Yao Meng, Andrew Kling, David L. Lubkeman, and Ning Lu	A Data-Driven Pivot-Point-Based Time-Series Feeder Load Disaggregation Method.	IEEE Transactions on Smart Grid
Rongxing Hu, Yiyan Li, Si zhang, Valliappan Muthukaruppan, Ashwin Shirsat, Mesut Baran, Wenyuan Tang, David Lubkeman, Ning Lu	MW-level PV powered microgrid energy management	2021 PES General Meeting
Victor Paduani, Lidong Song, Bei Xu, Dr. Ning Lu	PV power tracking control for providing ancillary services	2021 PES General Meeting
Ashwin Shirsat, Valliappan Muthukaruppan, Rongxing Hu, Ning Lu, Mesut Baran, David Lubkeman, Wenyuan Tang	Community-level PV powered dynamic microgrid energy management	2021 PES General Meeting
Quan Nguyen, Mallikarjuna R. Vallem, Bharat Vyakaranam, Ahmad Tbaileh, Xinda Ke, Nader Samaan	Controlling PV hybrid system for Black start	2021 PES General Meeting
Ahmad Tbaileh, Mallikarjuna R. Vallem, Quan Nguyen, Xinda Ke, Nader A. Samaan, George Stefopoulos, Xia Jiang	Controlling PV hybrid system for Black start	2021 PES General Meeting
H. Yu, M. A. Awal, H. Tu, Y. Du, S. Lukic and I. Husain	A Virtual Impedance Scheme for Voltage Harmonics Suppression in Virtual Oscillator Controlled Islanded Microgrids	*2020 IEEE Applied Power Electronics Conference and Exposition*
Asmaa Alrushoud, Catie McEntee, and Ning Lu	A Zonal Volt/VAR Control Mechanism for High PV Penetration Distribution Systems	2021 PES General Meeting
Long Qian, Hui Yu, Fuhong Xie, Wenti Zeng, Srdjan Lukic, Ning Lu, and David Lubkeman	Microgrid Power Flow Control with Integrated Battery Management Functions	2020 PES General Meeting
A. Alrushoud and N. Lu	Impacts of PV Capacity Allocation Methods on Distribution Planning Studies	2020 T&D
Jiyu Wang, Ning Lu, Sen Huang, and Di Wu	A Data-driven Control Method for Operating the Commercial HVAC Load as a Virtual Battery	2019 PES General Meeting

List of Publications - Submitted

1. Yiyan Li, Lidong Song, Si Zhang, Laura Kraus, Taylor Adcox, Roger Willardson, Abhishek Komandur, and Ning Lu, “TCN-based Spatial-Temporal PV Forecasting Framework with Automated Detector Network Selection,” https://arxiv.org/abs/2111.08809. submitted to IEEE Trans. Sustainable Energy.
2. Lidong Song, Yiyan Li, and Ning Lu. "ProfileSR-GAN: A GAN based Super-Resolution Method for Generating High-Resolution Load Profiles." arXiv preprint arXiv:2107.09523 (2021). Submitted to IEEE Trans. Smart Grid, under 2st round review
3. Mingzhi Zhang, Xiangqi Zhu, and Ning Lu, “A Data-driven Probabilistic-based Flexibility Region Estimation Method for Aggregated Distributed Energy Resources,” Submitted to IEEE Trans. Smart Grid. https://arxiv.org/abs/2110.07406.
4. 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,” submitted to 2022 PES General meeting. https://arxiv.org/pdf/2111.09464.pdf
5. Victor Paduani, Bei Xu, David Lubkeman, Ning Lu, “Novel Real-Time EMT-TS Modeling Architecture for Feeder Blackstart Simulations,” submitted to 2022 IEEE PESGM. https://arxiv.org/pdf/2111.10031.pdf
6. Hanpyo Lee, Han Pyo Lee, Mingzhi Zhang,Mesut Baran, Ning Lu, PJ Rehm, Edmond Miller, Matthew Makdad P.E., “A Novel Data Segmentation Method for Data-driven Phase Identification,” submitted to 2022 PES General Meeting. http://arxiv.org/abs/2111.10500
7. Si Zhang, Mingzhi Zhang, Rongxing Hu, David Lubkeman, Yunan Liu, and Ning Lu, “A Two-stage Training Strategy for Reinforcement Learning based Volt-Var Control,” submitted to 2022 PES General Meeting. https://arxiv.org/abs/2111.11987