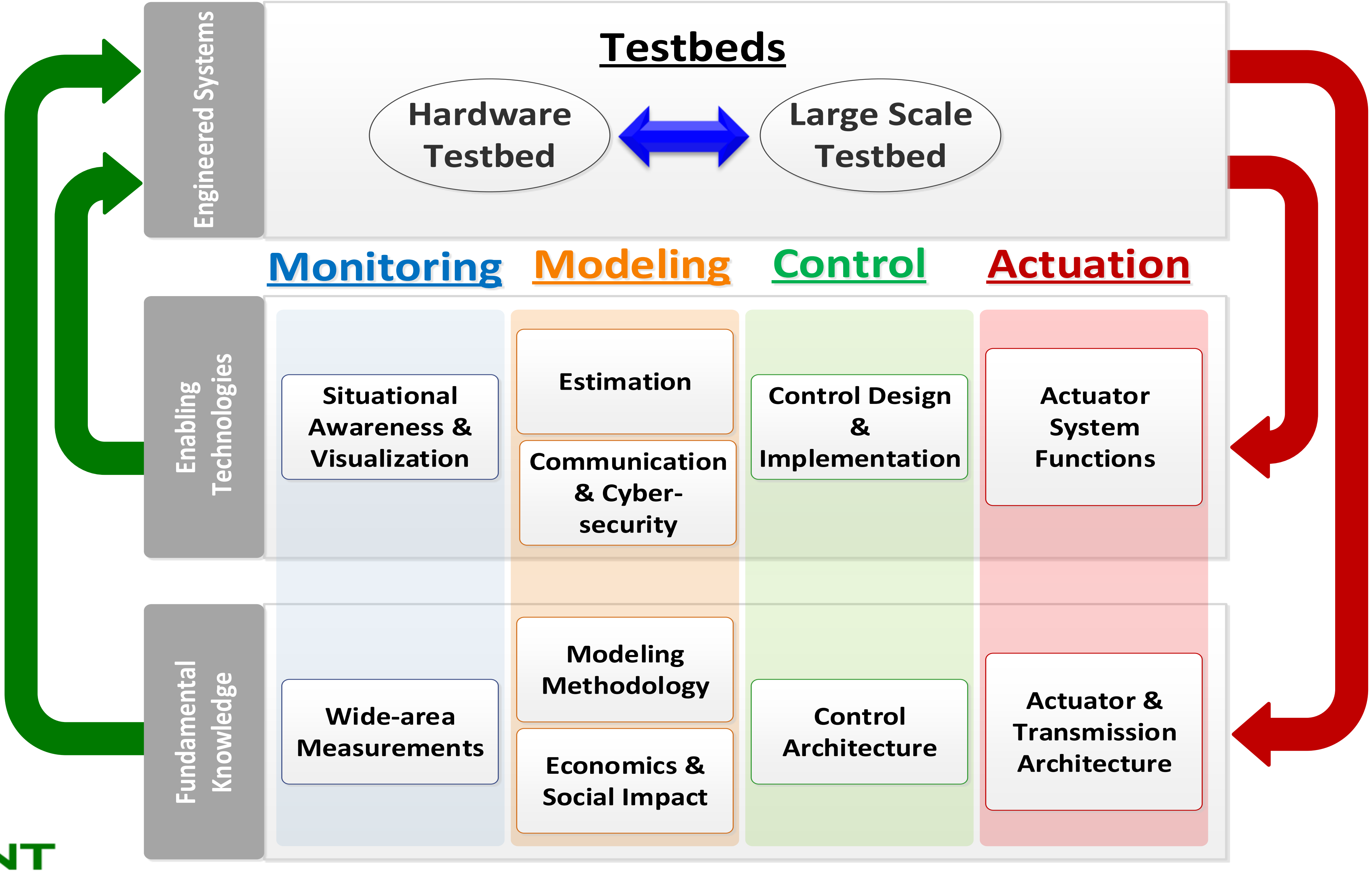
Engineered Systems Testbeds Overview

Fran Li (LTB lead),
Leon Tolbert (HTB lead)

NSF-DOE Site Visit

November 9, 2020

Systems Testbeds - Thrust Linkages



Technology demonstration in real-time environment

Demonstrate interoperability of multiple technologies in a designed, integrated platform

Testbeds show tangible benefit for how new technology and control would benefit the future electric grid.

Testbeds drive integrated research focus for Center

Provide system specifications for four thrusts

Scenarios show how closed loop controls and other center technology impact grid resiliency

CURENT

Systems Testbeds Intellectual Merit and Broader Impact

Intellectual Merit

- **LTB** has several different large simulation models including EI, ERCOT, WECC, and North America with HVDC overlay models that are verified with monitoring and measurement and represent future grids with high penetration levels of renewables.
- **HTB** has integrated power electronic based electric grid real-time emulation with actual power flow, measurement, communication, and control that can represent transmission level systems and distribution / microgrid systems.
- Visualization and real time system demonstrations show effectiveness of new monitoring and control.

Broader Impact

- Testbeds provide cyber physical vulnerability assessment tools for grid-related measurement, communication, and cyber equipment.
- **HTB** can represent other electrical systems (ship, plane, vehicle) and provides integrated power electronics and power system demonstration.
- **LTB** models can be used remotely by others to test new algorithms, models, and software.

Systems Testbeds Thrust Contributors

Faculty Participants:

Leon Tolbert, Fran Li, Fred Wang, Kevin Tomsovic, Kai Sun, Yilu Liu, Hector Pulgar, Hairong Qi, Stella Sun, Jian Huang (*UTK*)

Ali Abur, Hanoch Lev-Ari (*Northeastern*)

Joe Chow, Meng Wang, Jian Sun, Luigi Vanfretti (*RPI*)

Greg Murphy, Jesmin Khan, Mandoye Ndoye (*Tuskegee*)

Alex Stankovic (*Tufts*)

Research Staff Participants:

Jingxin Wang, Hantao Cui, Yunting Liu, Bob Martin (*UTK*)

Industry Partners:

EPB, ABB, GE, Dominion, TVA, PNNL, NREL, LLNL, ORNL, ISO New England, NYISO, MITRE, Danfoss, Eaton, OPAL-RT, National Instruments, Keysight, OSIsoft

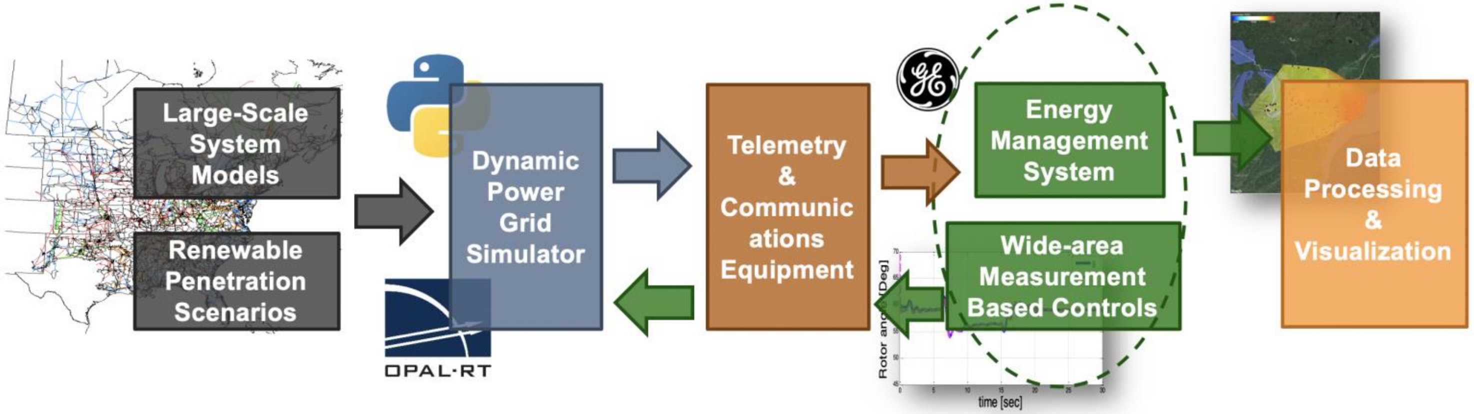
Large-scale Test Bed (LTB) Overview

Objective

To develop a real-time integrated cyber-physical platform for continuously simulating the operation of a power grid under small or large disturbances, with communication, wide-area monitoring, and control in the loop.

Challenges

1. Lack of an integrated software platform to continuously simulate power grid dynamics and mimic energy management and control.
2. Modular design to re-use software components for interoperability.
3. Need for an interactive web-based interface for running the simulations directly from a web browser, visualizing it and playing back.



LTB Roadmap

Generation I (Years 1-3)	Generation II (Years 4-6)	Generation III (Years 7-10)
Regional grid models with > 20% penetration of renewables and HVDC connections	Reduced North American system model with >50% penetration of renewables and HVDC connections	Large model of North American system with >80% renewables and HVDC connections
Model development for primary and secondary frequency and voltage controls in regional grids	Extension of frequency and voltage control models to North American grid and for damping control and transient stability control	Fully integrated system model of real time communication, coordinated control, actuators, monitoring and responsive load
Scaled down system models suitable for testing in RTDS and HTB; scenario development to include diverse system operating conditions	Scenario development for North American grid	Detailed scenarios for contingencies and cyber attacks sufficient to demonstrate resilience

CURENT

LTB Achievement Highlights

Software Platform Development

Previous years:

- **ANDES**: a Python-based simulator
- **DiME** (Distributed Messaging Environment): Rapid data streaming between asynchronous modules
- **LTBPMU** PMU and PDC simulators in the IEEE C37.118 protocol
- **CURENT system**: 1000-bus NA grid with EI, WECC & ERCOT integrated with HVDC overlay and 80% renewables
- **LTBNet**: Communication network emulator with 181-node communication network for NA

Year 9:

- Hybrid Symbolic-Numerical Framework
- Mass-Matrix-based DAE solver
- Solar and wind dynamic model
- Rapid DiME & visualization

2020 R&D 100 WINNER

Research Integration

Previous years:

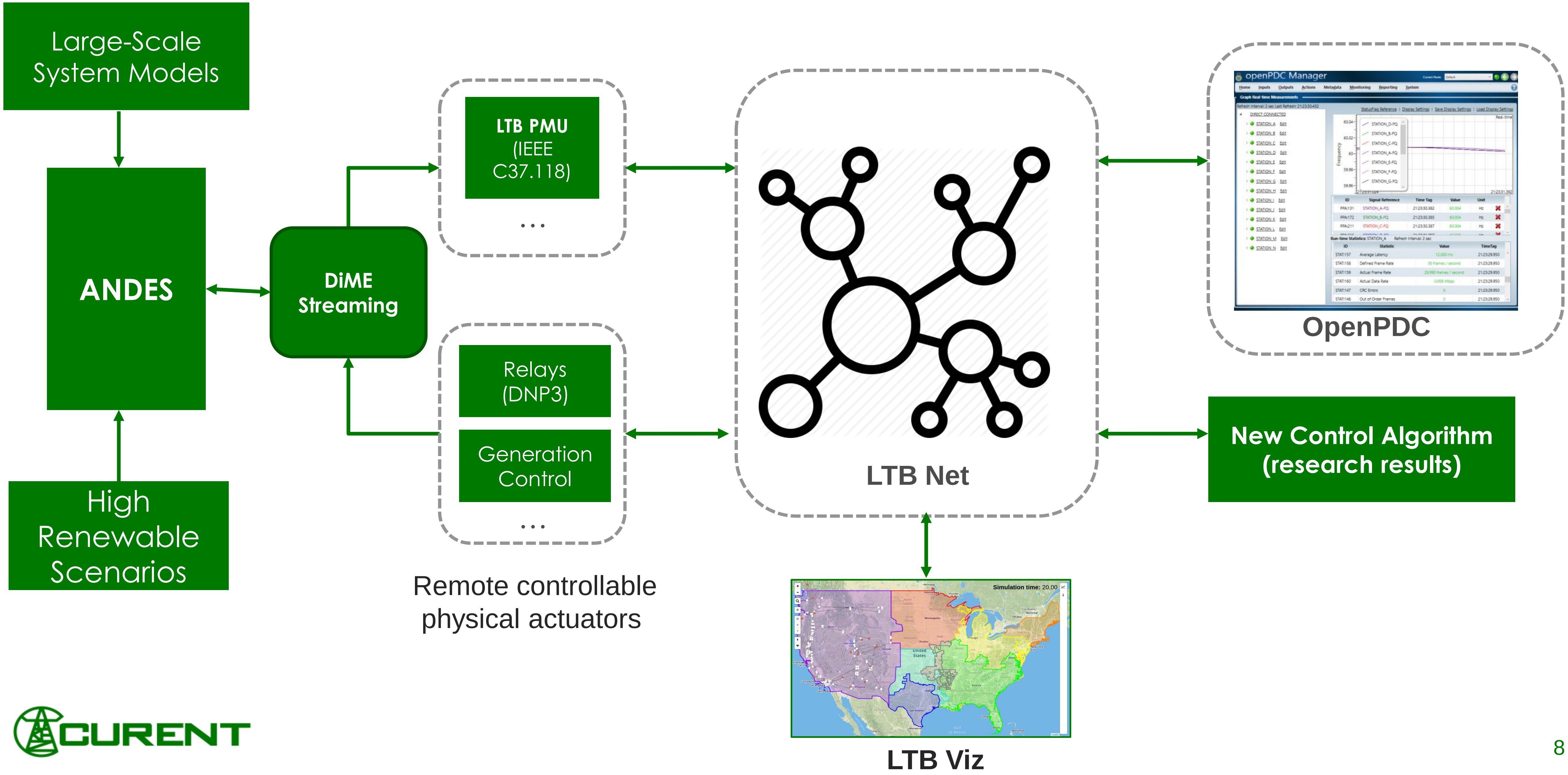
- Energy Mgmt.: Robust LAV-assisted dynamic state estimator
- Wide-Area Monitoring & Control
  - Online voltage stability assessment
  - Hierarchical and game theory-based voltage control
  - Extended AGC
  - System separation control
  - DFIG power reserve control and damping control
  - Inertia sharing using multi-terminal HVDC
  - Replay attacks on PMUs
- Model Predictive Control-based AGC
- Wide-area damping control under DDOS attack

Year 9:

- Market based cyber attack detection
- VAR optimization based on PSO

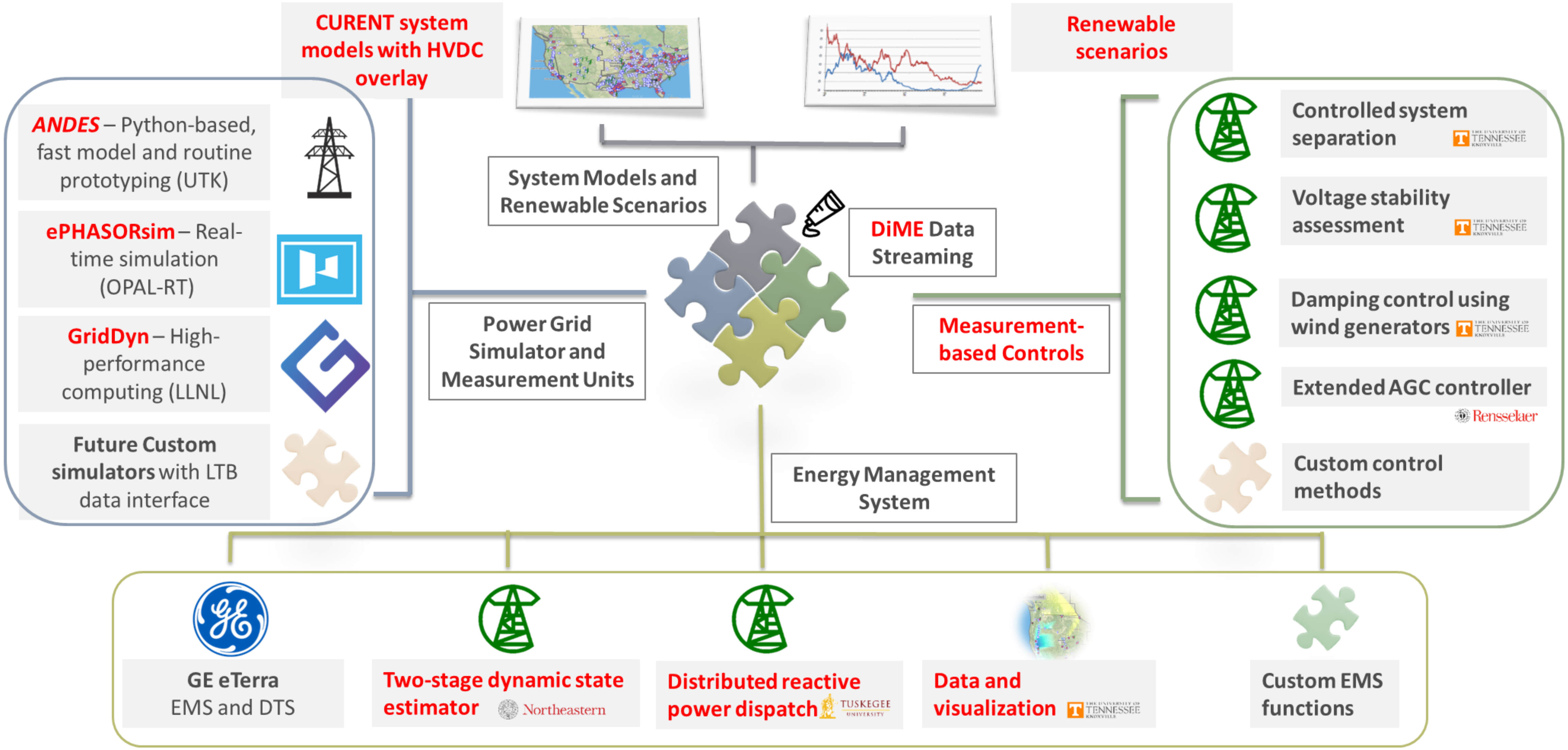
CURENT

LTB Data Flow



CURENT

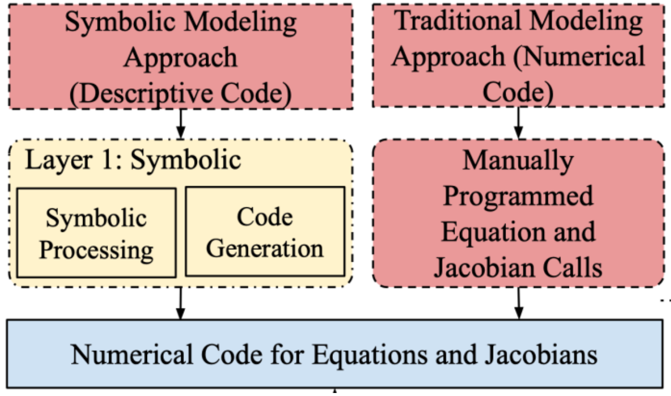
LTB Architecture



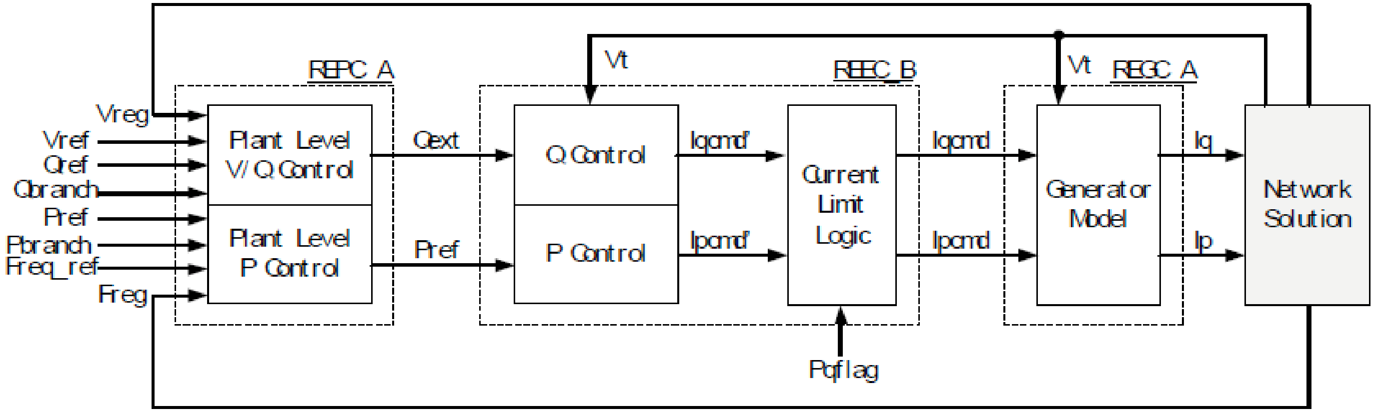
CURENT

Year 9: Core Research

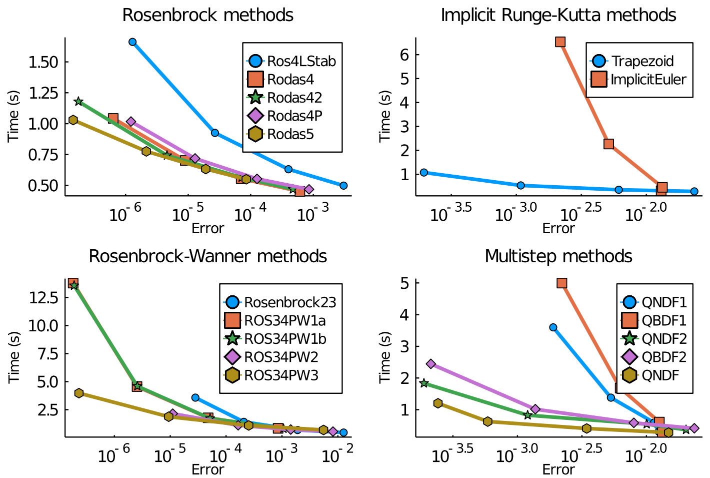
Hybrid symbolic-numeric framework for power systems modeling and analysis



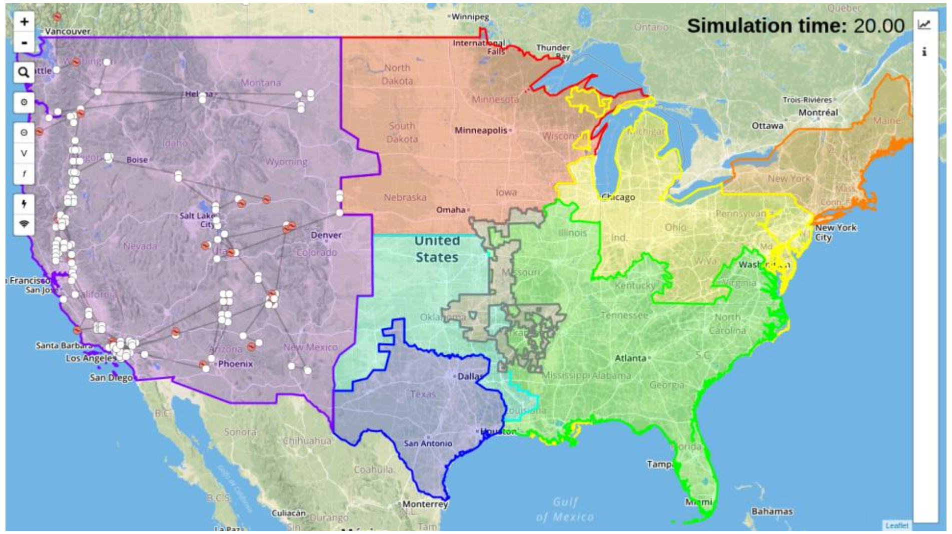
High-fidelity modeling of solar PV and wind generators



Mass-Matrix-based DAE Solver for power system transient stability simulation



Rapid distributed data streaming service and visualization

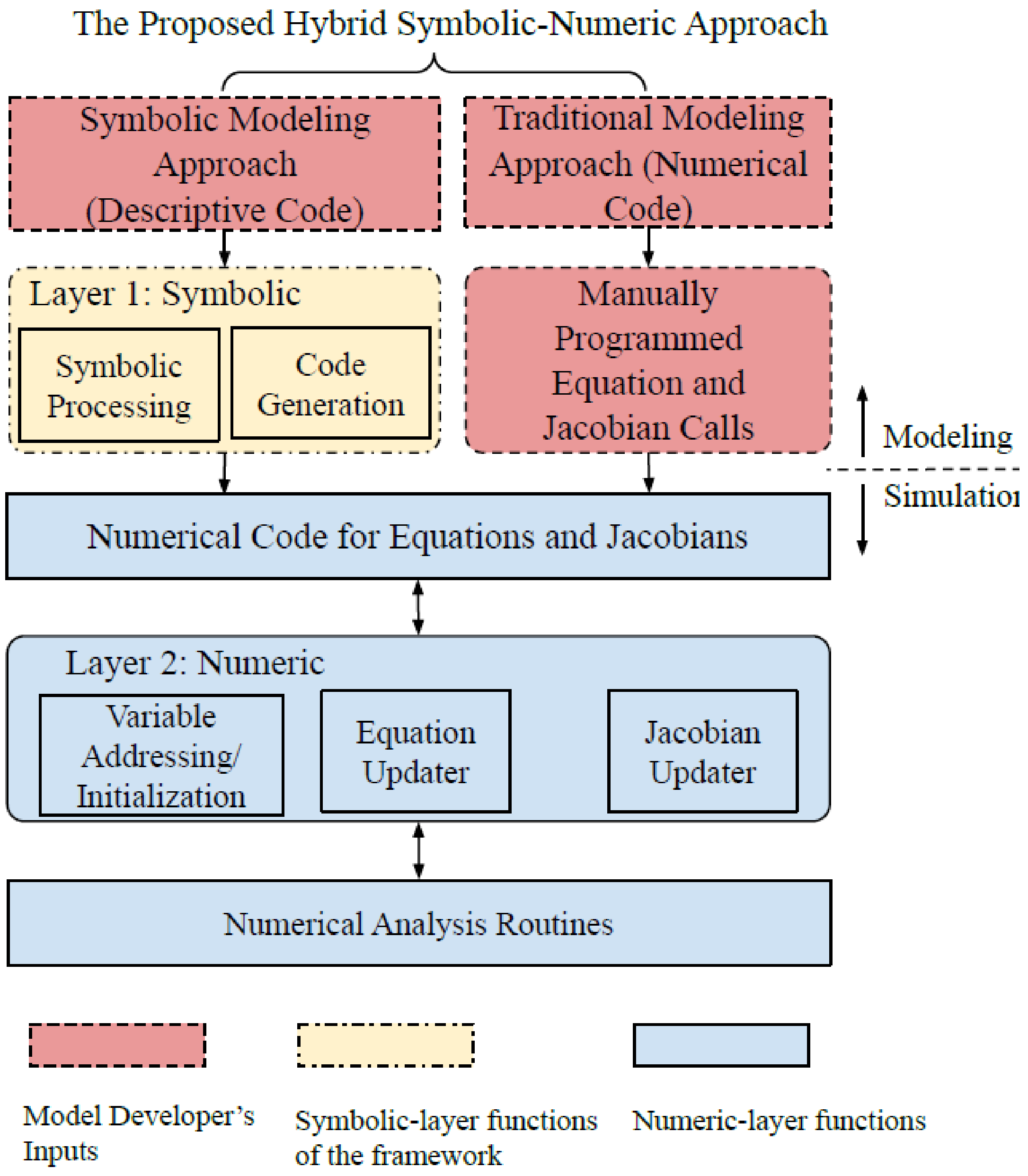


CURENT

Hybrid Symbolic-Numeric Framework (1)

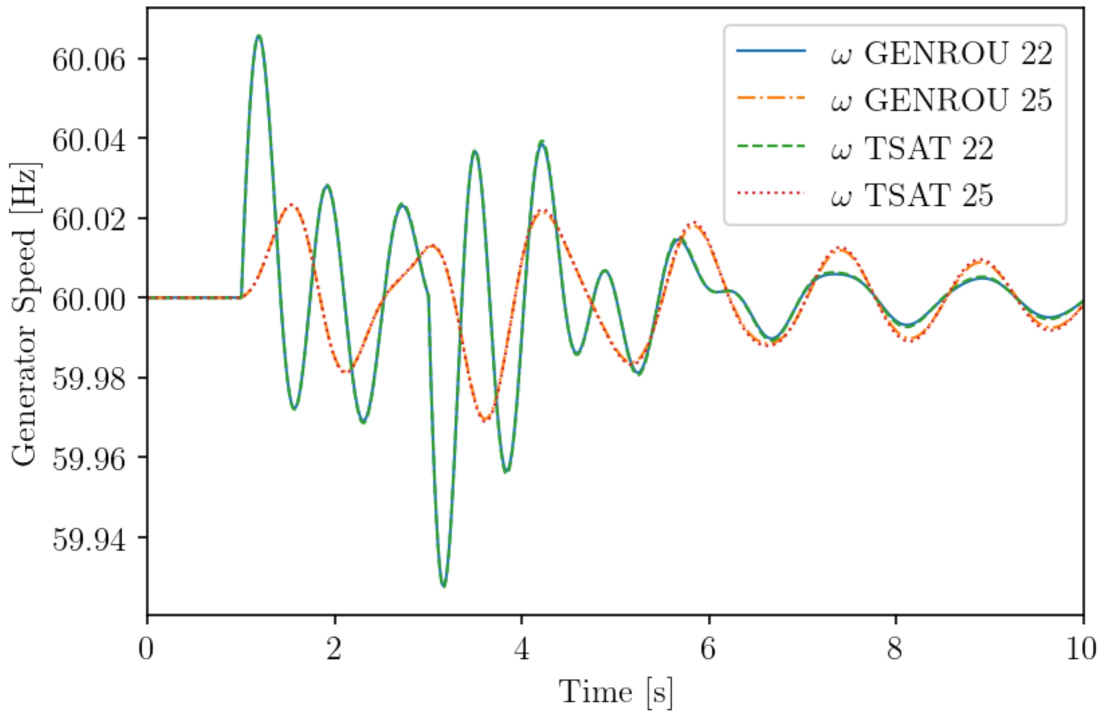
- Open-Source Release and Public Announcement of ANDES, a Python-based Software Tool for Symbolic Power System Modeling and Numerical Analysis

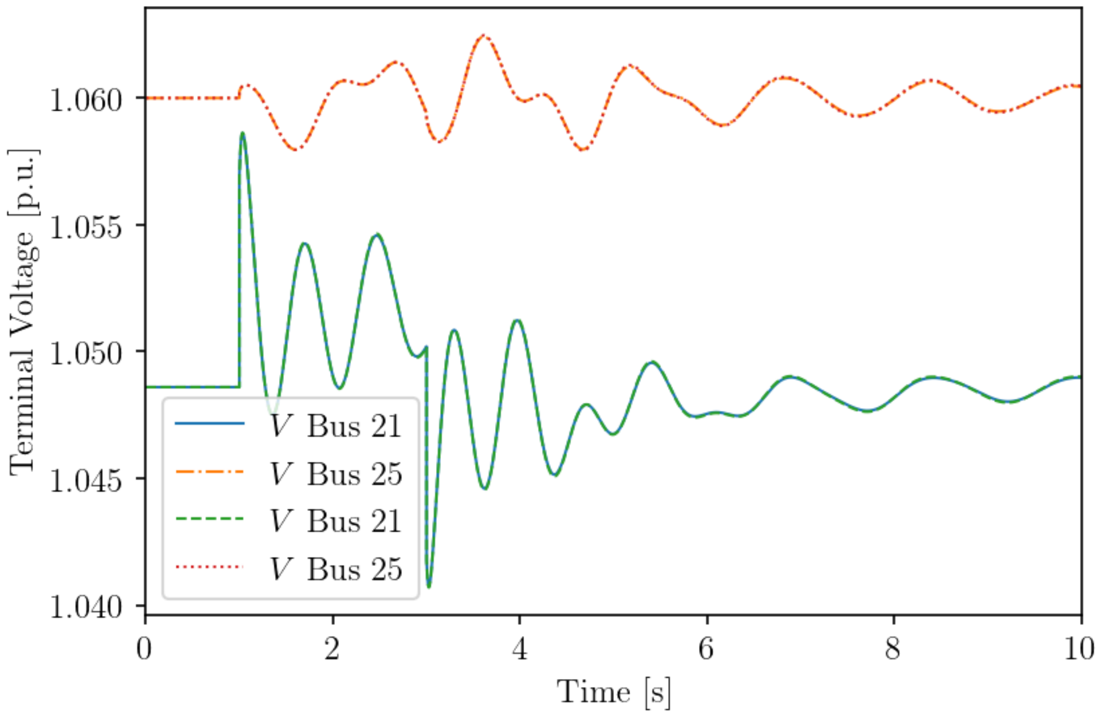
- Architecture of symbolic versus numeric framework



Hybrid Symbolic-Numeric Framework (2)

- NPCC 140-bus system
  - Using models GENCLS, GENROU, IEEEX1, and TGOV1
  - Perfect match with TSAT results





NPCC system response following Line 1-2 trip at 1 sec. and reconnect after 2 sec.

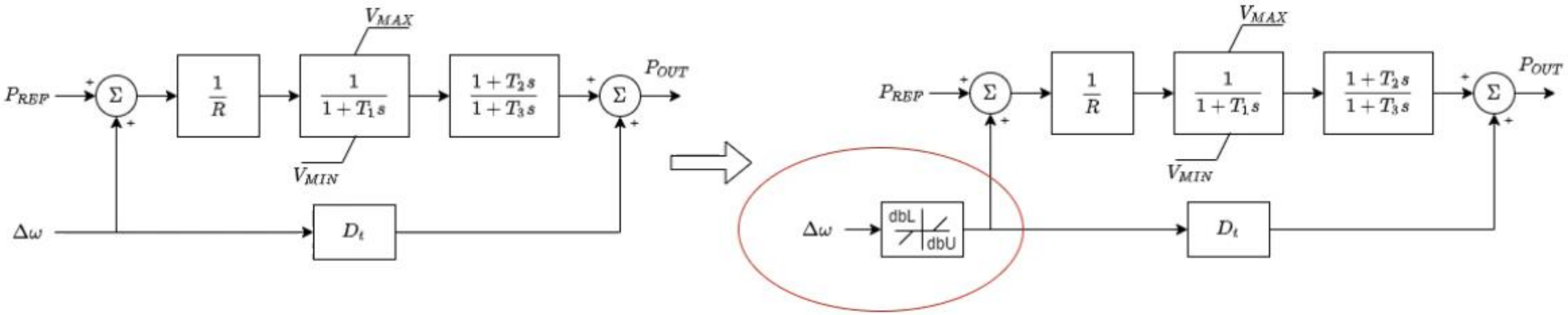
CURENT

LTB Demo 1: Symbolic Descriptive Modeling

Symbolic Descriptive Modeling with CURENT LTB

This video demonstrates symbolic descriptive modeling through an example.

We will implement a deadband component for the TGOV1 turbine governor model.



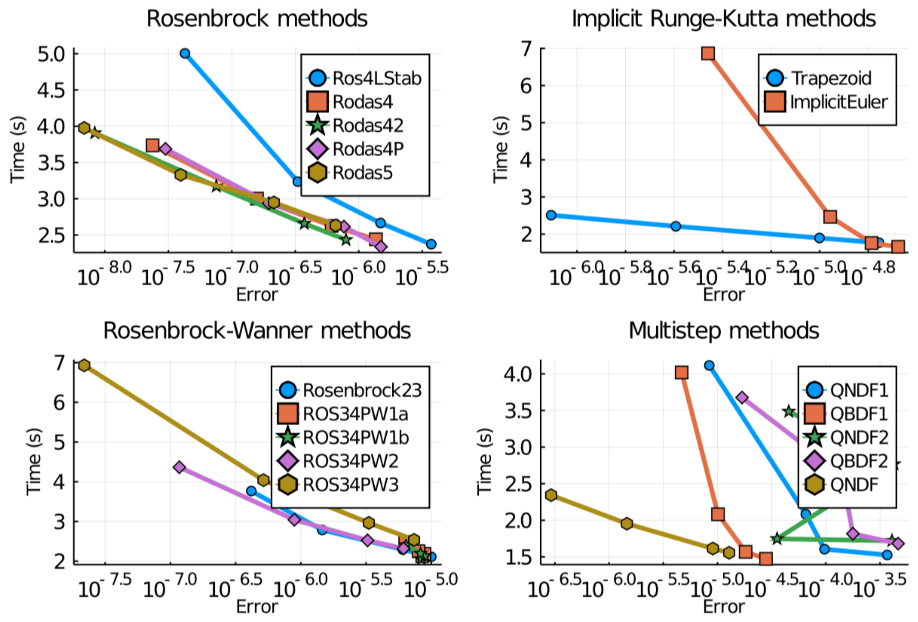
Mass-Matrix-based DAE Solver for Transient Stability

- Proposed a Mass-Matrix Formulation

$$\underbrace{\begin{bmatrix} \boldsymbol{M_x} & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{0} \end{bmatrix}}_{\boldsymbol{M}} \begin{bmatrix} \dot{\boldsymbol{x}} \\ \boldsymbol{0} \end{bmatrix} = \begin{bmatrix} \hat{\boldsymbol{f}}(\boldsymbol{x}, \boldsymbol{y}, \boldsymbol{u}) \\ \boldsymbol{g}(\boldsymbol{x}, \boldsymbol{y}, \boldsymbol{u}) \end{bmatrix},$$

where $\boldsymbol{M}$ is a $(n+m) \times (n+m)$ possibly-diagonal matrix with its upper-left $n \times n$ block being $\boldsymbol{M_x}$. $\hat{\boldsymbol{f}}$ ($\hat{\boldsymbol{f}} : \mathbb{R}^{m+n+o} \Rightarrow \mathbb{R}^n$) is chosen based on $\boldsymbol{f}$ and determines the diagonality of $\boldsymbol{m}$.

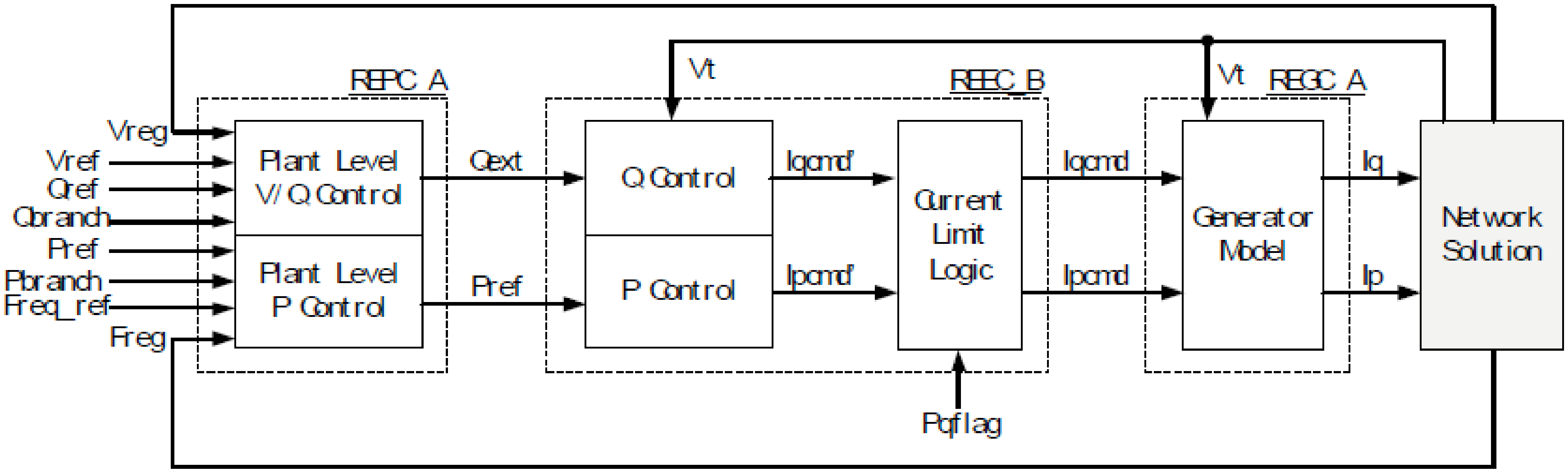
Example: low-pass filter $\dot{x} = (u - x)/T$, where u is the input and T is the time constant. Models want the filter to become a pass-through when T=0.



Solver benchmarks using a dynamic 2,000-bus system

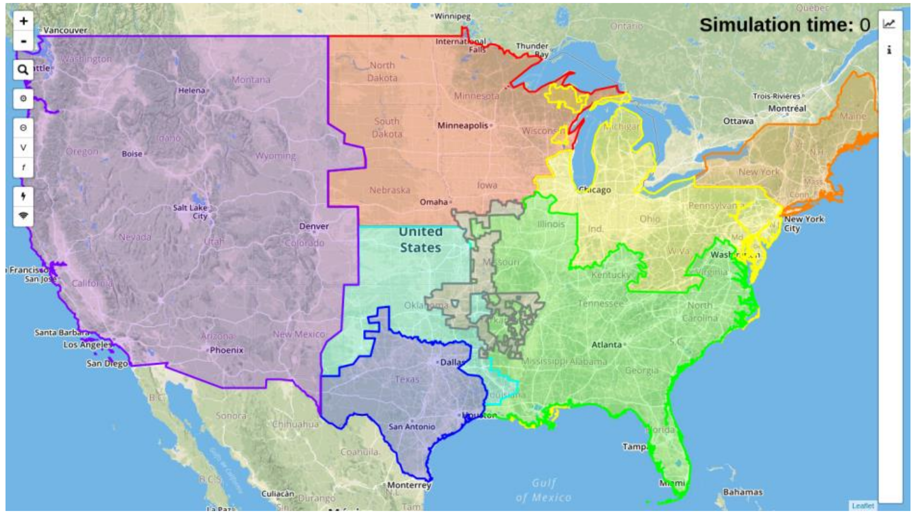
High-Fidelity Modeling of Renewables

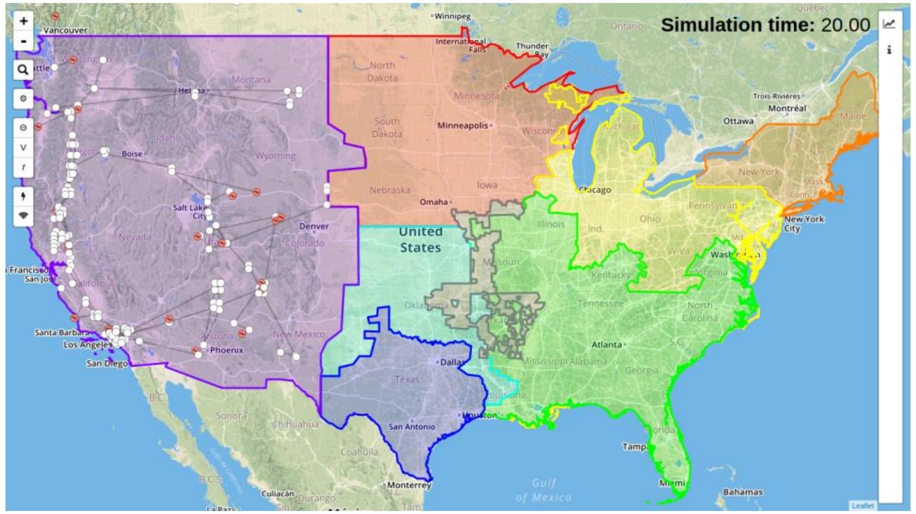
- Industry Renewable Energy Models
  - Solar PV and Type 4 wind stability models:



Rapid Data Streaming and Visualization

- Implemented a rapid data streaming solution
  - For overcoming the bottleneck of the previous Python-based solution when used for large-scale systems (over 1,000 buses)
  - Server is rewritten in C
  - Supports listening on multiple addresses of TCP, IPC and Websocket protocols
  - Supports Python, MATLAB and WebSocket clients
  - Regional visualization





Users of LTB

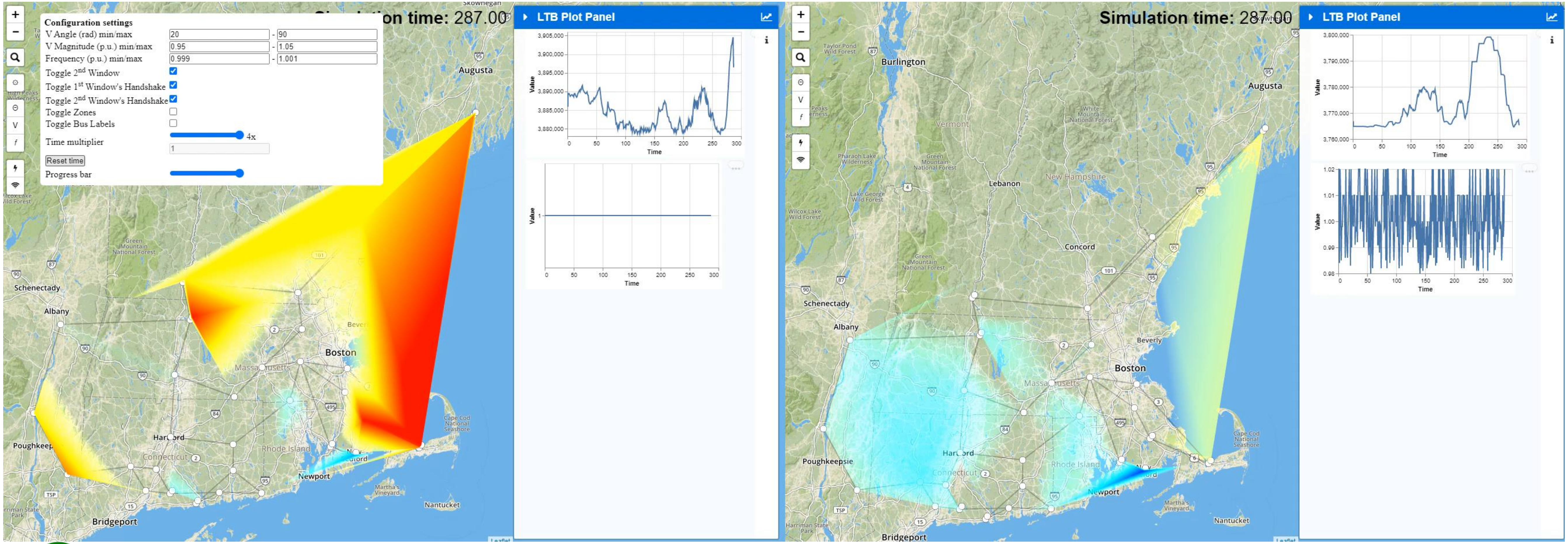
- Two software maintenance & support agreements signed
  - Missouri University of Science and Technology (signed in 2020)
  - University of Denver (signed in 2020)
- Two national lab users
  - Lawrence Livermore National Laboratory
  - Idaho National Laboratory
- Played a critical role to obtain funding in

DOE CEDS project: WISP (UTRC + UTK)	2019-2022	$2.9 M
DOE SBIR project (Achillea Research + UTK)	2020-2021	$186 K
NSF EPCN project (H. Pulgar + F. Li, UTK)	2020-2022	$210 K
NREL AOP project (NREL + UTK)	2020-2022	$350 K
	Total:	**$3.65M**

CURENT

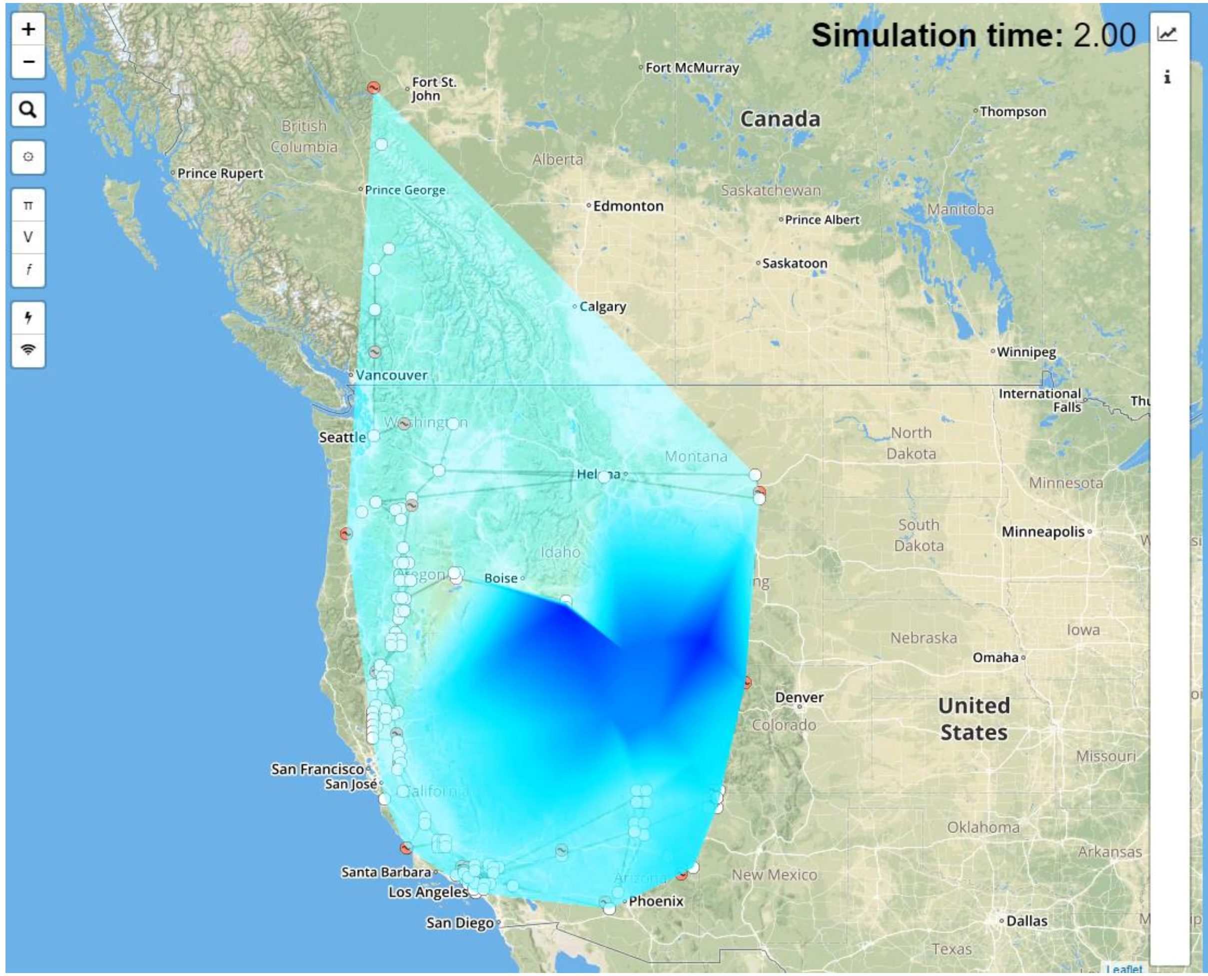
LTB Demo 2: VAR Optimization based on Particle Swarm Optimization (Tuskegee)

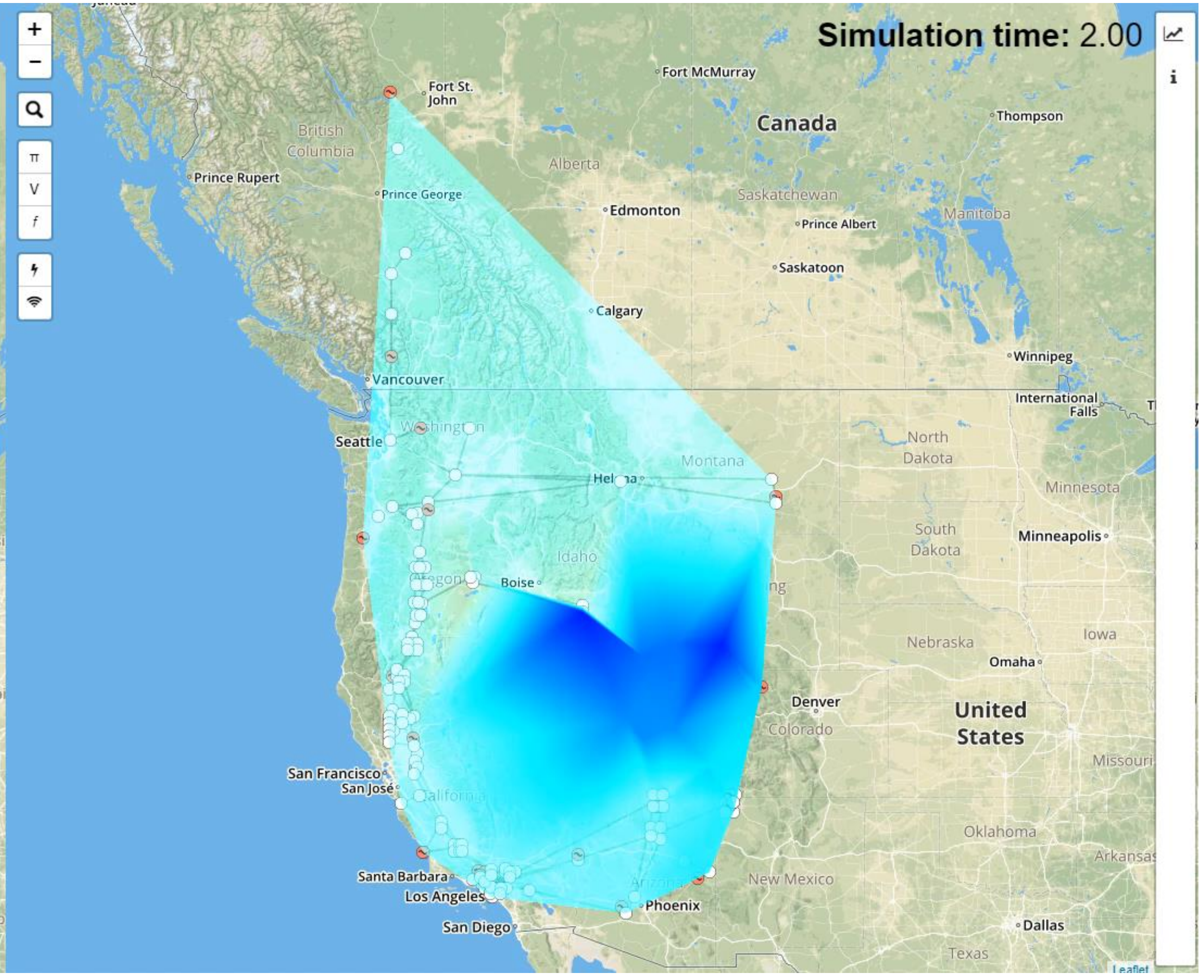
Minimizing the total cost while maintaining voltage within 0.98-1.02 p.u.



LTB Demo 3: Defending Congestion Attacks on Market Prices (WISP Project with RTRC)

Two congestion attacks happen at 38 *sec* and 64 *sec*.





CURENT

LTB Plan for Year 10

	Year 10
Grid Model and Renewable Scenario Development	• Develop load models for large-scale systems
Platform Development	• Refine visualization for various use cases • Improve the computational efficiency of the simulator
Demonstrations	• Detailed cyber-physical attack scenarios to demonstrate resilience

CURENT

LTB Future Research Directions Beyond Year 10

	Beyond Year 10
Platform Development	• Link with HTB to provide co-simulation/emulation • Implement the economic dispatch and market model • Co-simulation with distribution systems or microgrids
Applications	• Enhanced user interface to achieve training capabilities
Project/Proposal Support	• Support externally funded projects to maintain sustainability

CURENT

HTB Demonstration Plan and Roadmap

Generation I (Years 1-3)	Generation II (Years 4-6)	Generation III (Years 7-10)
Hardware implementation of power electronics based emulators, including large wind / solar / storage farm emulation.	Implementation of sensing, monitoring, actuation, and protection in real-time.	Coordinated high penetration renewable (>80%) grids using closed-loop dynamic measurement-based controls.
Integrate PMU/FNET data into HTB.	Integrate with real-time simulation.	Automatic real-time grid reconfiguration through remedial action mode switching.
Multiple load and scenario demonstrations (multi-terminal HVDC, hybrid AC/DC, multi-area oscillation and control, high renewable energy penetration).	Scenario demonstrations (multiple HVDC links between wide areas, major tie line and wind farm outage dynamic effects, coordinated power flow control over large distances, demonstrate system resilience to attacks, energy storage impact).	Ultra-wide-area coordinated real-time communication, control, and protection on a system hardened against coordinated cyber attack. Microgrids and distribution systems with inverter-connected sources, loads, and energy storage.

CURENT

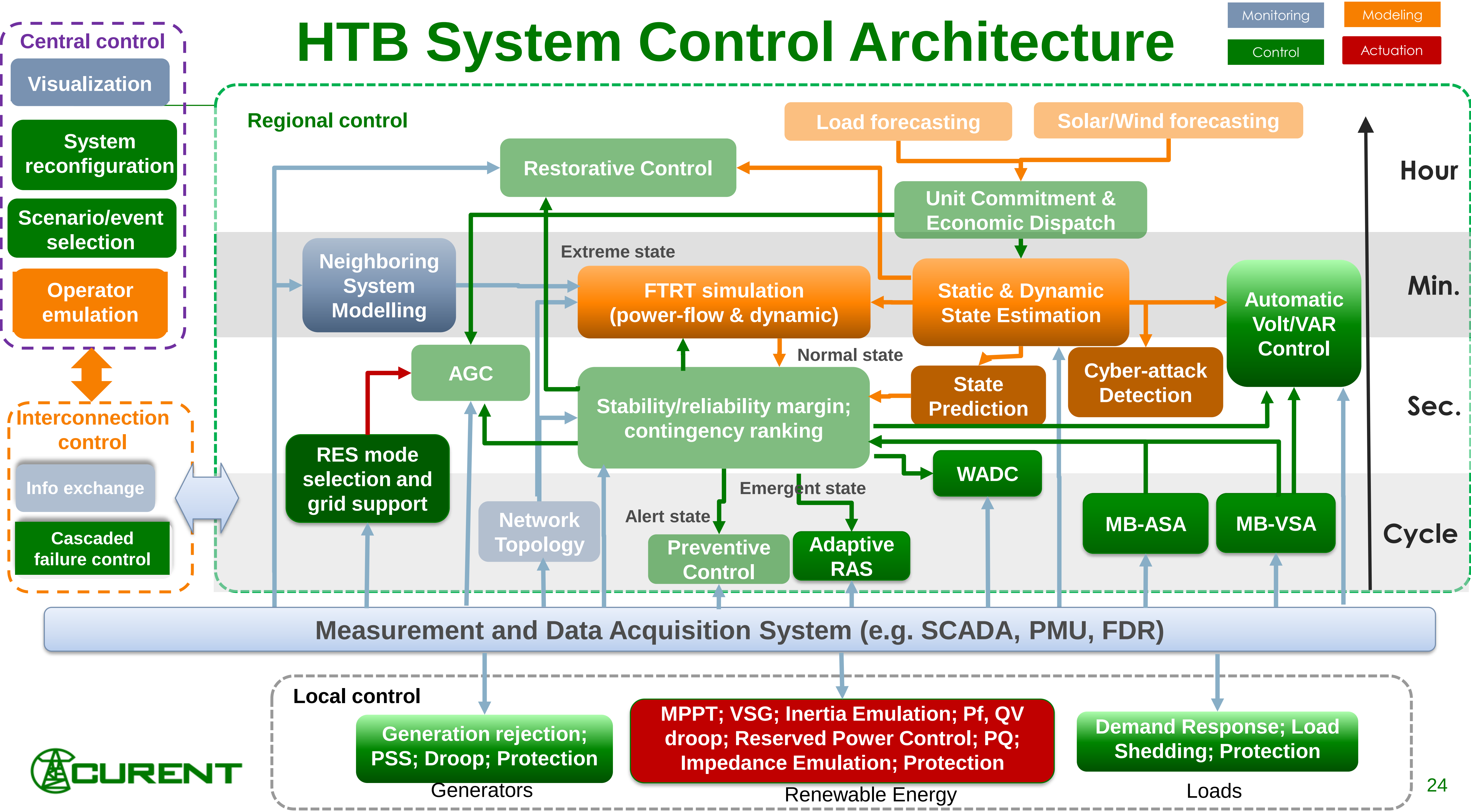
Year 9 HTB Achievements Summary

- Security/stability assessment based system control architecture completed and implemented on HTB
- New more detailed WECC HTB model developed that includes >80% renewables, energy storage, HVDC overlay
- Expand HTB emulation capability including motor drive emulator and its frequency support function, data center power supply emulator, EV charger emulator
- Secure-cloud framework developed to demonstrate communication / measurement cybersecurity
- Microgrid controller demonstrated on HTB with automatic reconfiguration in both grid-connect and island mode prior to field deployment in EPB microgrid
- Use of HTB integral for receiving several successful DOE and ARPA-E grants.

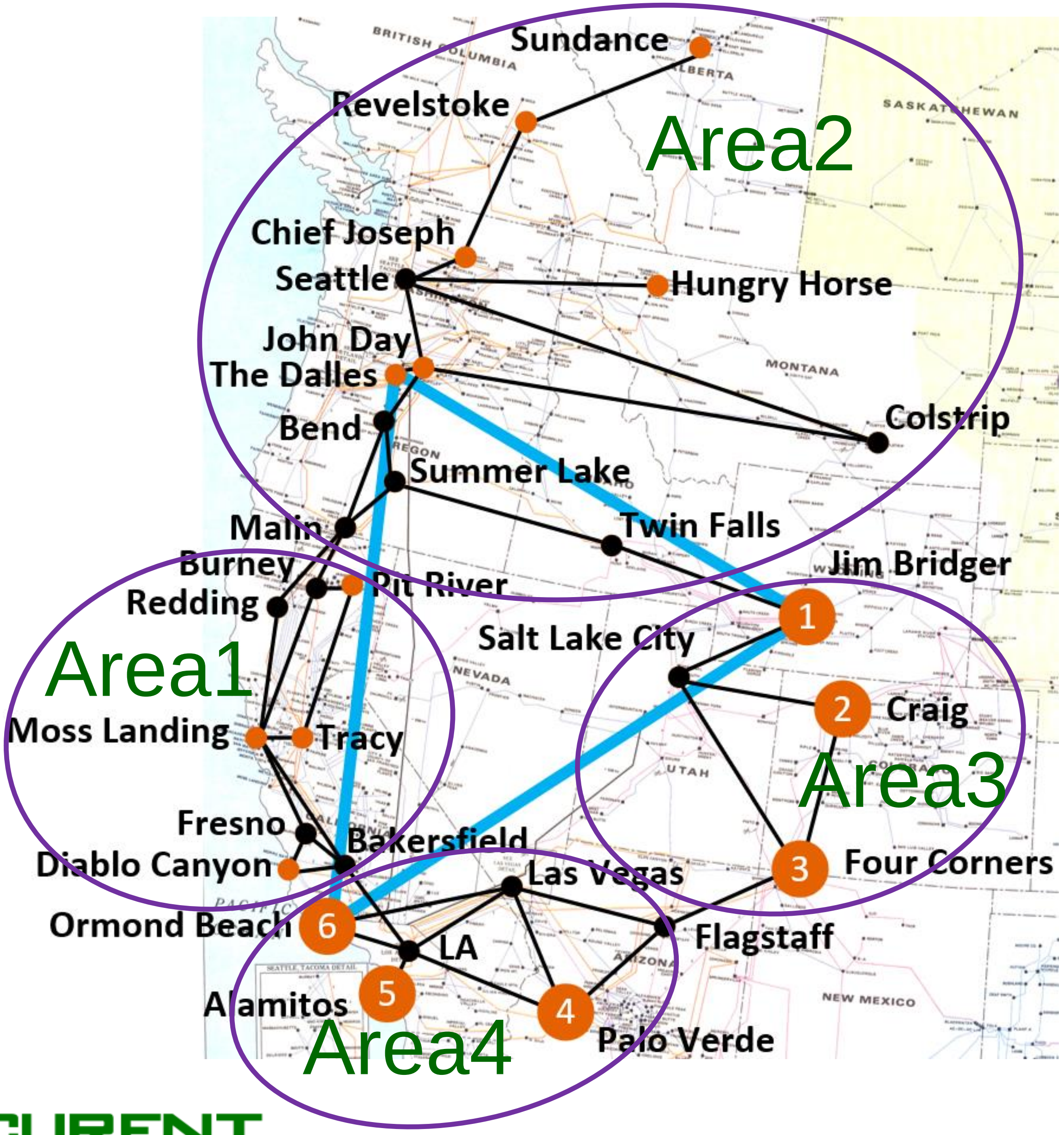
CURENT's HTB Area cabinets use inverters to represent sources, lines, loads, and storage

CURENT

HTB System Control Architecture

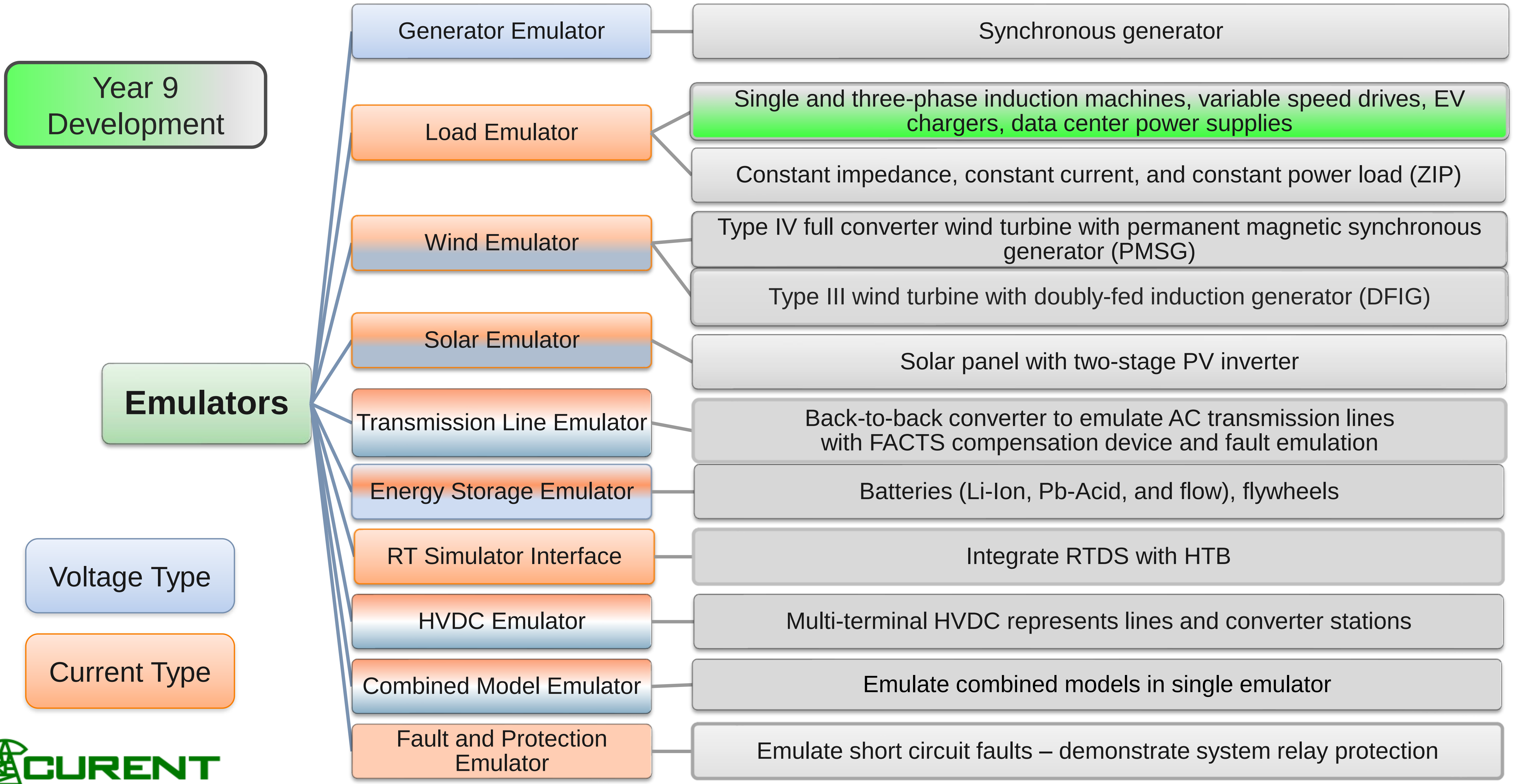


New HTB WECC Model Developed in Year 9



- Model incorporates >80% renewables, storage, and responsive load
- Area 3 and Area 4 are implemented in HTB
- Area 1 and Area 2 are implemented in RTDS
- Two amplifiers are implemented to connect RTDS and HTB

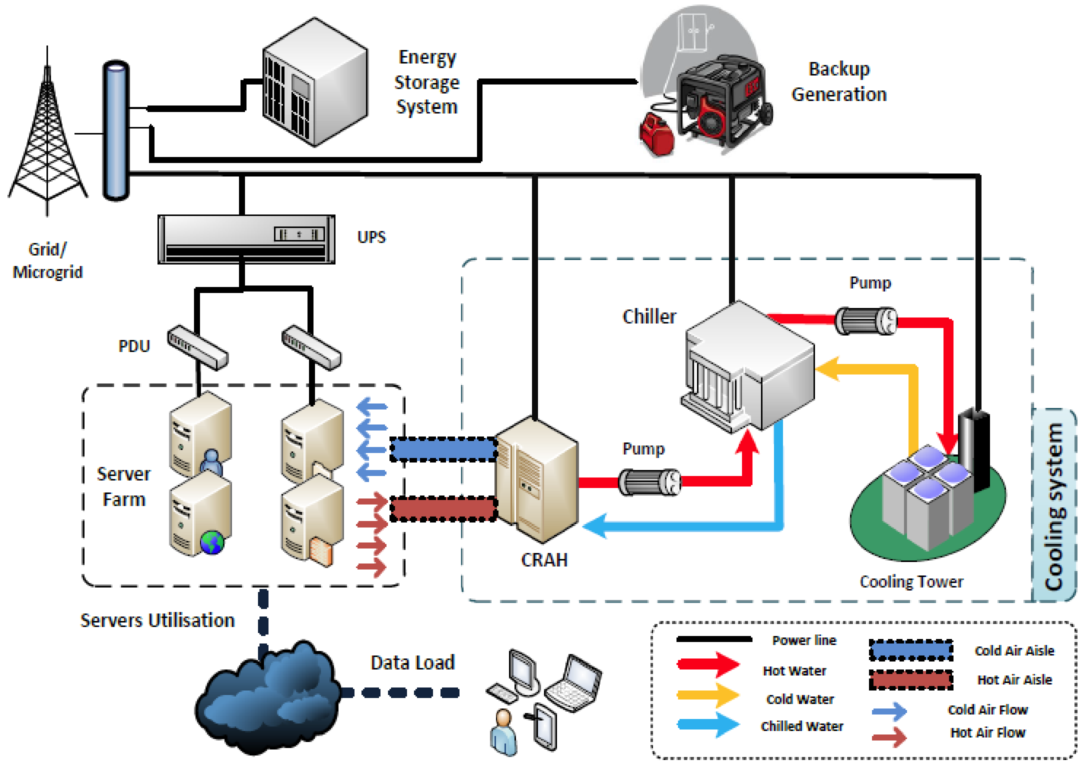
Emulator Development Summary



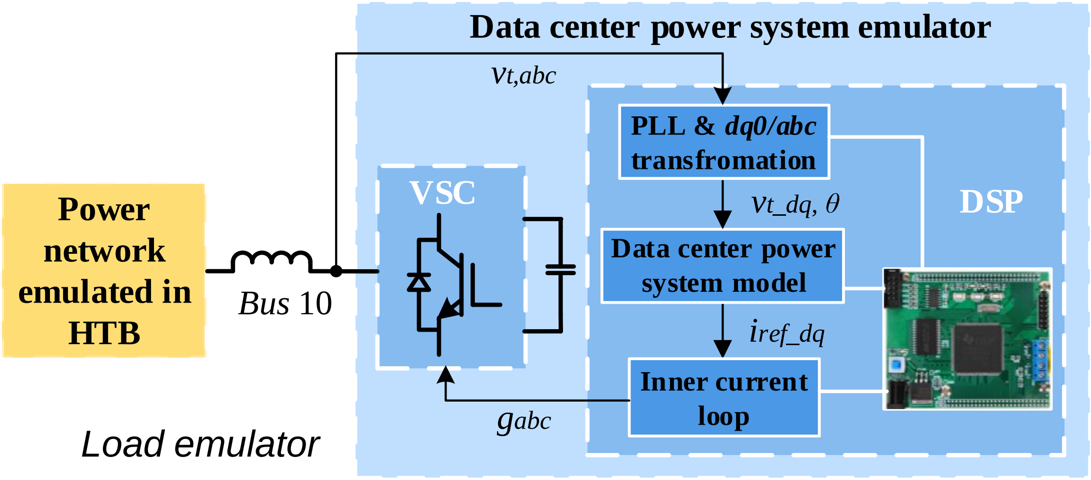
CURENT

Data Center Load Emulator

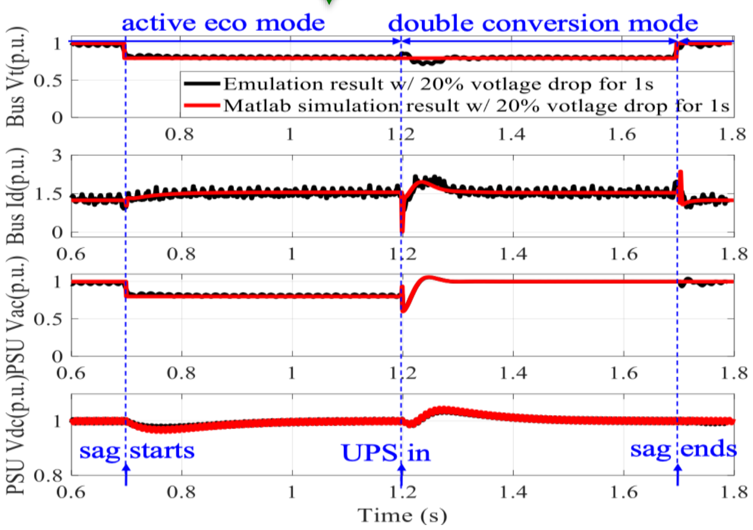
- Emulator developed to reflect data center load including computing, cooling, and other ancillary loads.



Typical data center structure



Dynamic performance

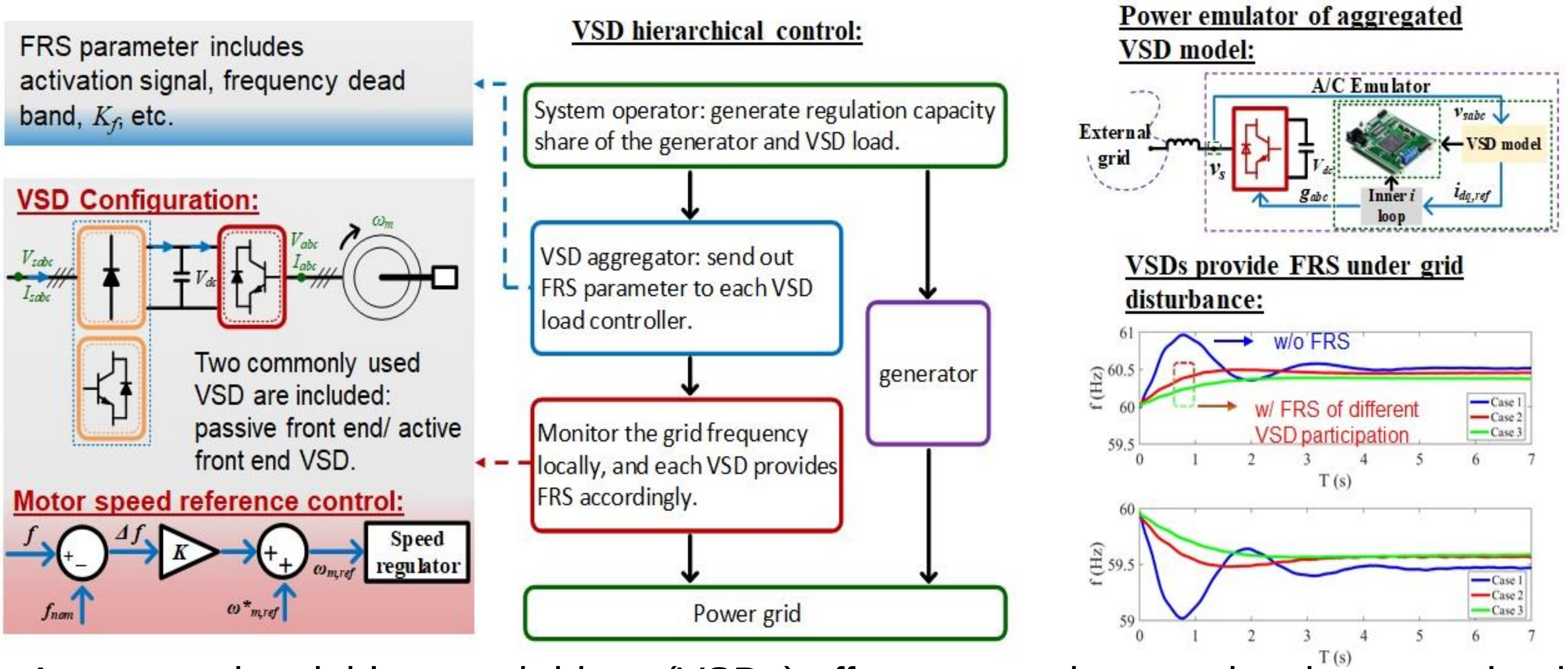


Typical structure of class 1 data center power supply system

ANSI/BICSI-002, Data center design and implementation best practices, 2014.

CURENT

VSD Loads Hierarchical Control for Grid Frequency Support

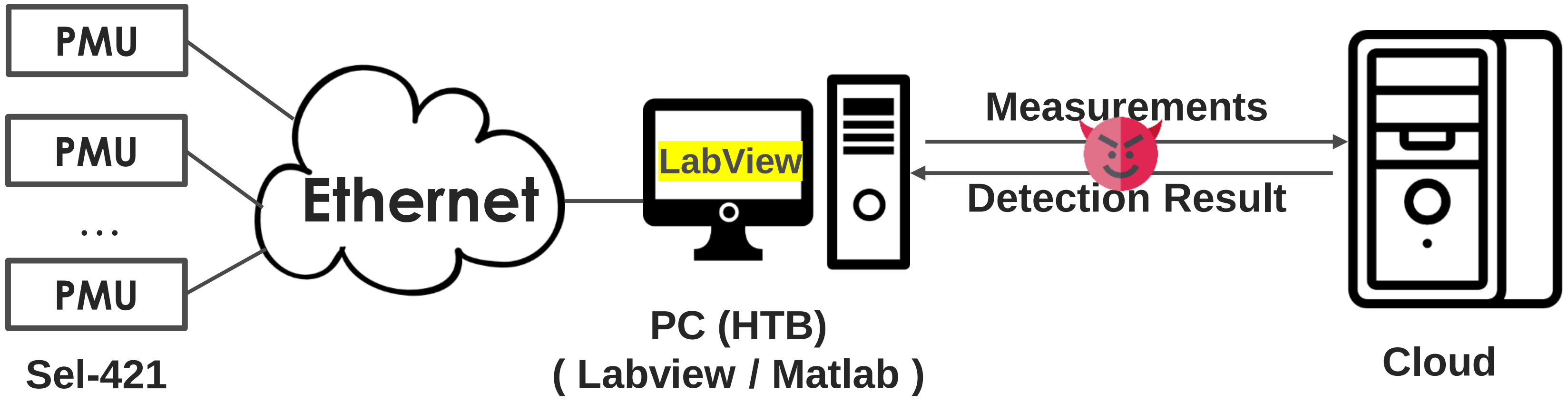


➤ Aggregated variable speed drives (VSDs) offer opportunity to make short-term load changes to provide frequency regulation services to the grid.

CURENT

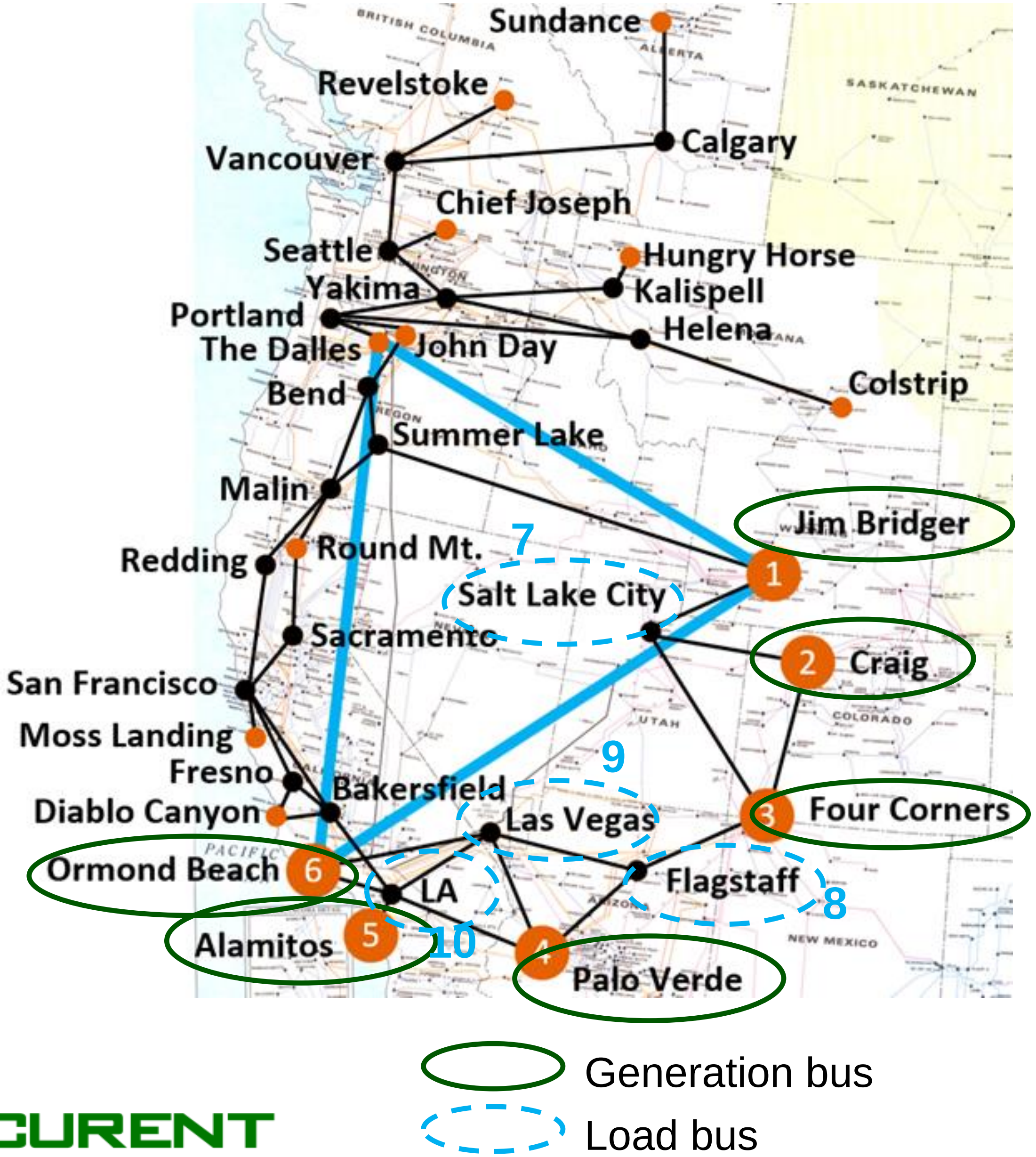
Deep Learning Based Event Detection with Secure Cloud-Framework for HTB

- Develop a novel method for enabling early, accurate, and robust detection, recognition, and temporal localization of multiple types of events in power systems.
- **Stronger Cloud Connection**
  - Optimize the application-layer communication protocol of the HTB-Cloud connection.
  - Separate update can be performed on HTB without a reboot of the Cloud.
- **Abnormal Response**
  - The two parties (HTB, Cloud) share a secret key.
  - If cyberattack detected by either the HTB and/or Cloud, the HTB and Cloud use the secret key to generate a new TCP port number and establish a new connection.



CURENT

Demo 1: VSD Providing Primary Frequency Support



1. **VSD frequency regulation for normal summer temperature.**

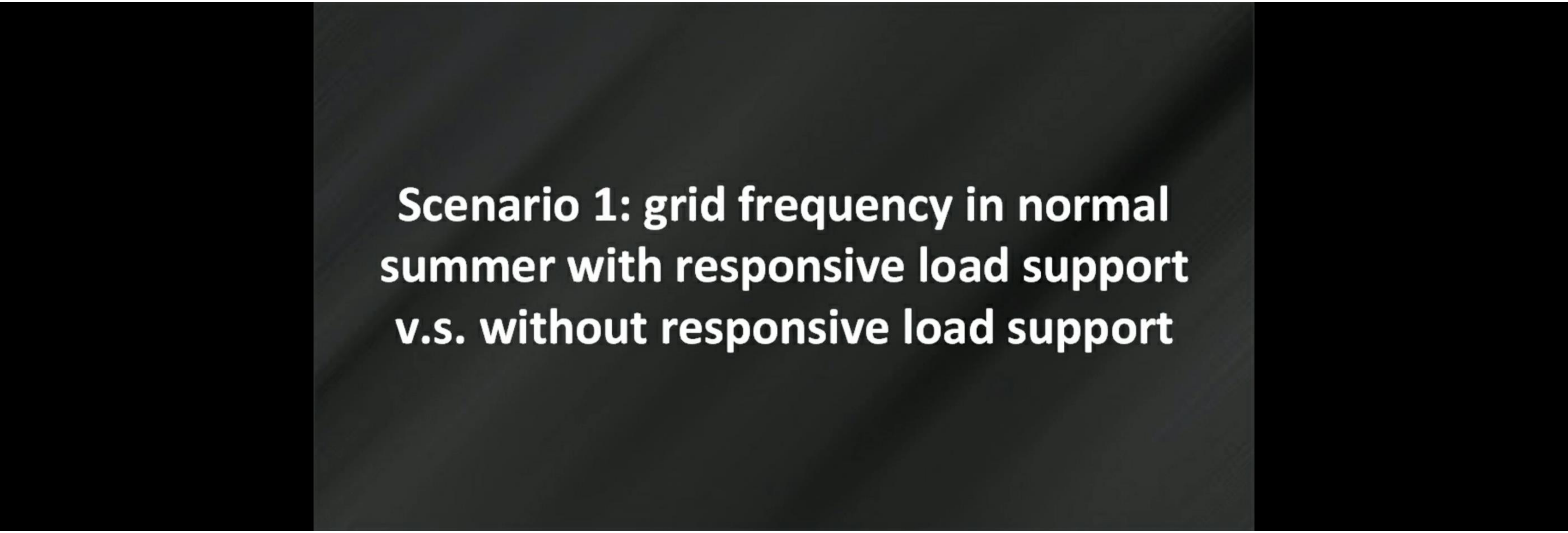
- Primary frequency control also provided by VSD loads based on projected VSD load available for participation in utility-determined load change requests.

2. **Comparison between the hot summer case and normal summer case.**

- The difference between these two cases is the percentage of available power reserve provided by the VSD load in the hot summer is significantly lower than that in the normal summer.

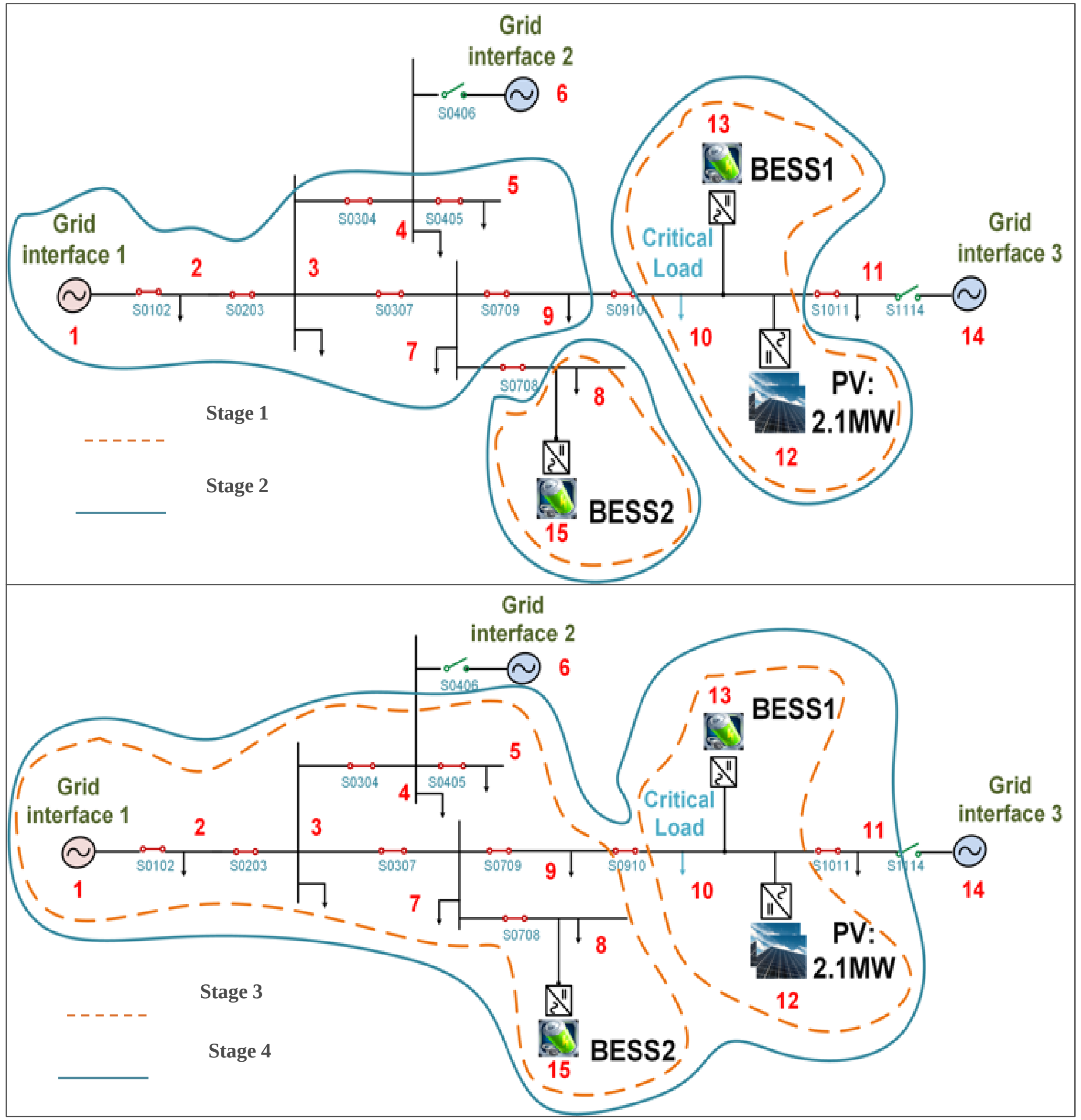
CURENT

Demo 1: VSD Providing Primary Frequency Support



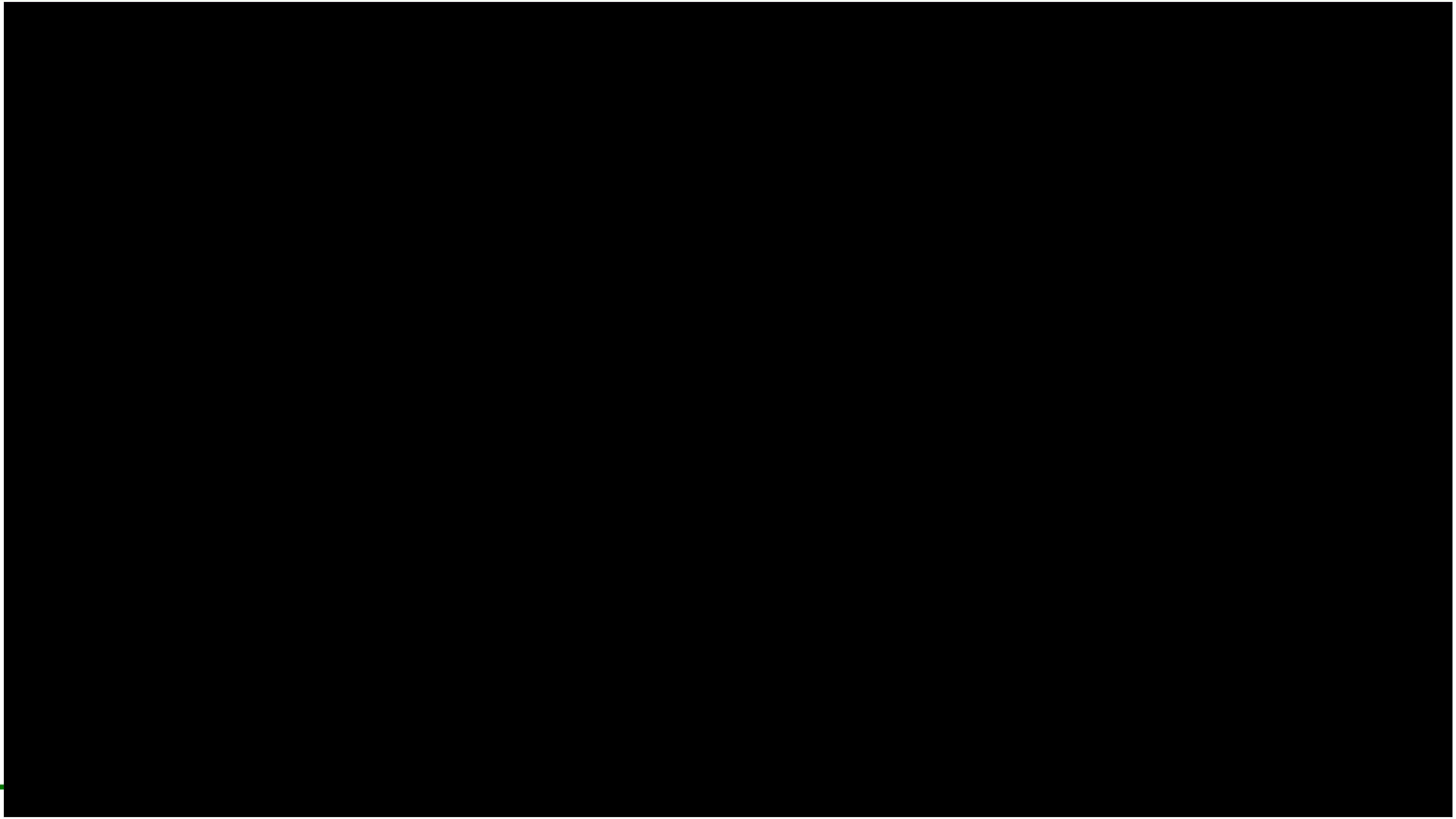
CURENT

Demo 2: Microgrid Controller for Distribution System with Multiple Islands and Dynamic Boundary



- CURENT developed a microgrid controller implemented on EPB's electrical distribution system in Chattanooga
- Controller first implemented on HTB to check its functions:
  - PQ balance
  - Black start
  - Planned and unplanned islanding
  - Dynamic boundary with multiple islands
  - Resynchronization and reconnection

Demo 2: Microgrid Controller for Distribution System with Multiple Islands and Dynamic Boundary



HTB Plans for Year 10

	Year 10
System model and emulation development	• Further evaluation of CURENT system security control paradigm in HTB. • Develop grid-forming controller that simultaneously considers the aspects of dc-link stability and ac grid interface stability of PV and battery-connected sources. • Verification of power electronic load models including EV chargers, data center power supplies, LED lighting
Hardware construction	• Extend cloud-enabled machine learning event detection method to be adapted to other applications.
Scenario demonstrations	• Energy storage and power electronics connected sources and loads grid impacts. • Detailed scenarios for contingencies and cyber attacks sufficient to demonstrate resilience. • Evaluate grid impacts of high penetration of PV in distribution systems, and their ability to provide ancillary services.

CURENT

HTB Future Research Directions Beyond Year 10

- Link with LTB to provide transmission and distribution co-simulation and emulation
- Test and validate electric vehicle motor drive and EV charging designs by UTK and others – HTB can emulate various motor loads or EV chargers
- Platform for ship and aircraft electric systems
- Microgrid control and protection development – several new and continuing projects
- Vulnerability assessment for grid-related measurement, communication, and cyber equipment
- Generate data for grid models developed by DOE National Laboratories and others

Acknowledgements

This work was supported primarily by the ERC Program of the National Science Foundation and DOE under NSF Award Number EEC-1041877 and the CURENT Industry Partnership Program.

Other US government and industrial sponsors of CURENT research are also gratefully acknowledged.