CURENT
CENTER FOR ULTRA-WIDE-AREA RESILIENT ELECTRIC ENERGY TRANSMISSION NETWORKS

Changing Testing and Simulations Needs for Grid Modernization

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New Mexico EPSCoR Smart Grid

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TUSKEGEE

CURENT – An NSF/DOE ERC

- Selected by National Science Foundation (NSF) and Department of Energy (DOE) from a few hundred proposals across all engineering disciplines.
- Base budget: $4M/year for up to 10 years. Leveraged funding: $7M/year
- First and only ERC devoted to power transmission.
- Four universities in the US (UTK, RPI, NE, TU)
- Industry partnership program (36 members as of Fall 2018)
- Center began Aug. 15th 2011.
- CURENT Students: ~140 graduate and ~75 undergraduate

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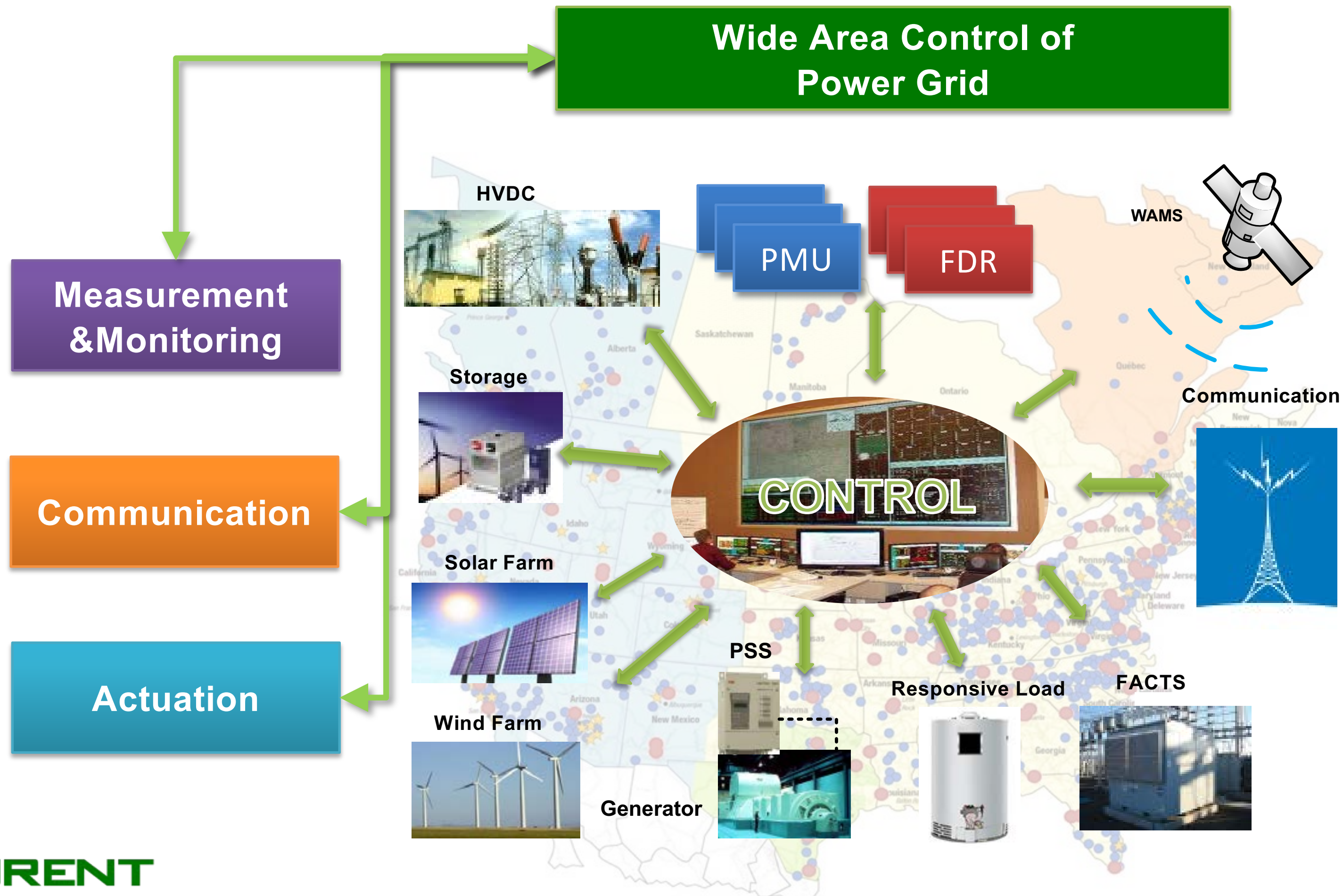
What is CURENT?



Research Roadmap

Year 1~3	Year 4~6	Year 7~10
Generation I	Generation II	Generation III
Regional grids with >20% renewable (wind, solar), and grid architecture to include HVDC lines	Reduced interconnected EI, WECC and ERCOT system, with >50% renewable (wind, solar) and balance of other clean energy sources (hydro, gas, nuclear)	Fully integrated North American system with >50% energy (>80% instantaneous) inverter based renewable resources (wind, solar) and balance of conventional (hydro, gas, nuclear)
System scenarios demonstrating a variety of seasonal and daily operating conditions	Grid architecture to include UHV DC lines connecting with regional multi-terminal DC grids, and increased power flow controllers	Grid architecture to include UHV DC super-grid and interconnecting overlay AC grid and FACTS devices
Sufficient monitoring to provide measurements for full network observability and robustness against contingencies, bad topology or measurement data	System scenarios demonstrating complete seasonal and daily operating conditions and associated contingencies, including weather related events on wind and solar	Controllable loads (converter loads, EV, responsive) and storage for grid support
Closed-loop non-local frequency and voltage control using PMU measurements	Full PMU monitoring at transmission level with some monitoring of loads	Fully monitored at transmission level (PMUs, temperature, etc.) and extensive monitoring of of distribution system
Renewable energy sources and responsive loads to participate in frequency and voltage control	Fully integrated PMU based closed-loop frequency, voltage and oscillation damping control systems, and adaptive RAS schemes, including renewables, energy storage, and load as resources	Closed loop control using wide area monitoring across all time scales and demonstrating full use of transmission capacity and rights-of-way
		Automated system restoration from outages

CURENT Control and Coordination Architecture

Resilience and scalability by

- Distributed – renewables, grid, storage, and demand as active control participants
- Measurements – learning and adaptive, data-driven
- Modularized and hierarchical – global signals distributed with context
- Sharing resources – reduced impact of uncertainty

Figure 1: NIAC Resilience Construct

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Testbeds as a Central Organizing Feature for Research

- Future simulation and testing needs
- Emphasis on integrative research at CURENT
  - Large Scale Testbed
  - Reconfigurable Grid Emulator – Hardware Testbed
- Resilience concepts and testing needs

Changing Electric Power System

- Large central generation
- Rotating machines
- Passive transmission
- Small number of asynchronous sensors
- Hierarchical communications
- Costs driven
- Reliability focus considering equipment outages

- Small distributed generation
- Inverter interfaced
- Actively controlled T&D
- Ubiquitous synchronized sensing
- Open network
- Market (transactive) driven
- Reliability and resilience focus considering a wide variety of disturbances

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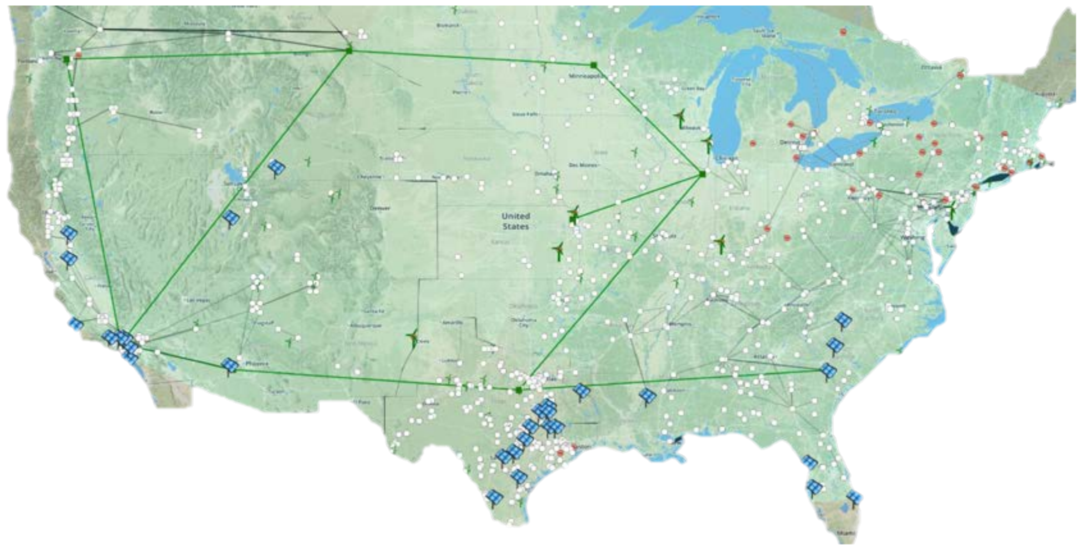
Challenges for Future Grid Modeling and Simulation

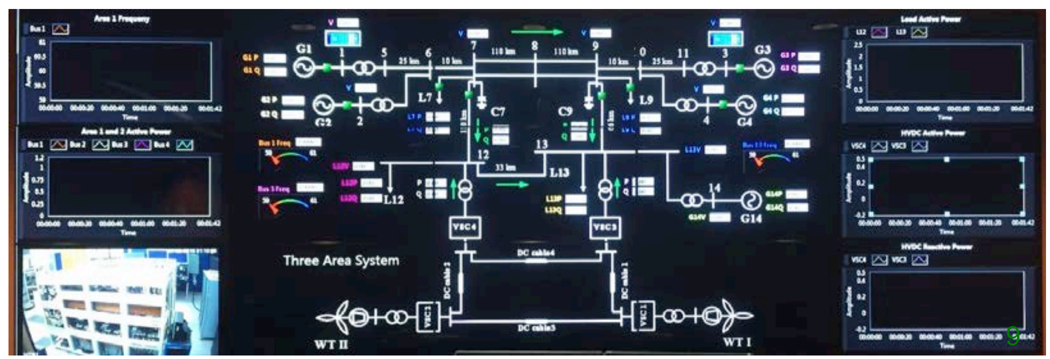
- **Increasing number of power electronic interfaced devices**
  - High speed response of inverters
  - Loss of electromechanical coupling that has familiar dynamic characteristics
  - New load characteristics
  - Understanding restoration
  - Protection issues
- **Emerging importance of communication systems**
  - Wide area closed loop controls
  - Open communication networks
  - Cybersecurity concerns
  - New contingencies
- **More actively controlled distribution – increasingly difficult to separate transmission and distribution studies**
  - Modeling issues – e.g., unbalanced flows, dynamic models in distribution, time varying load characteristics
  - Microgrids
  - Protection systems
  - Scaling problems
- **Performance requirements for both reliability and resilience**
  - Scenarios and required modeling is an open question

CURENT Testbed Projects

- **Large Scale Testbed (LTB)**: Virtual Grid Simulator with an Energy Management and Control System (Matlab based and Commercial-tool based)



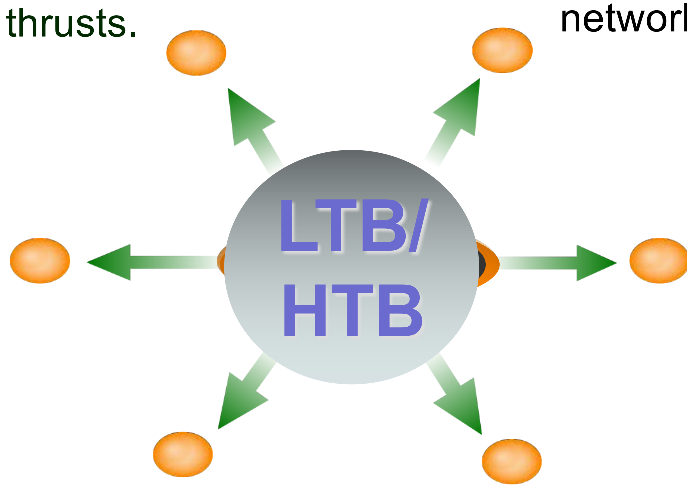
- **Hardware Testbed (HTB)**: Grid Emulator Development and Real-time Scenario Demonstration
- **Regional and National Power Grid Models**



Engineered System Testbed Objectives

Provide research platforms
for testing thrust technologies,
especially modeling and control thrusts.

Study ways to increase the transmission capability, presently constrained due to network security considerations.



Test different power electronics technologies and system architectures
for improving power flow and reliability.

Develop scenarios to evaluate resilience with high penetration of renewable energy sources, responsive loads, and energy storage on the future grid.

Include real-time communication networks, real-time control,
protection, cyber security, and actuation.

Demonstrate CURENT-developed controls,
wide-area responsive load,
and wide-area renewable generation.

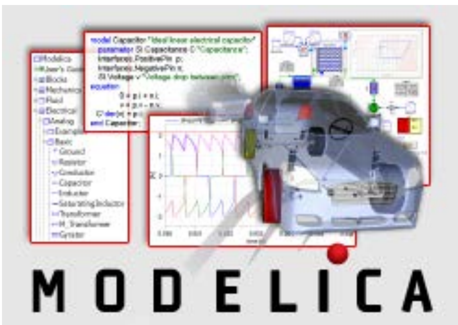
Background: Why the CURENT LTB?

- **Motivations for Large-scale Test Bed (LTB)**
  - To provide a closed-loop, real-time testing environment where advanced energy management and control functions over the communication network can be prototyped
  - To represent real-world measurement devices and actuator models that has sensing, actuating and communication capabilities
  - To provide a fully controllable and interactive cyber-physical simulation environment with renewable generation and power electronic interface models
  - To provide off-the-shelf large-scale dynamic test systems with high penetration of renewables

- LTB = Integrated Simulation Platform + Large-scale System Models

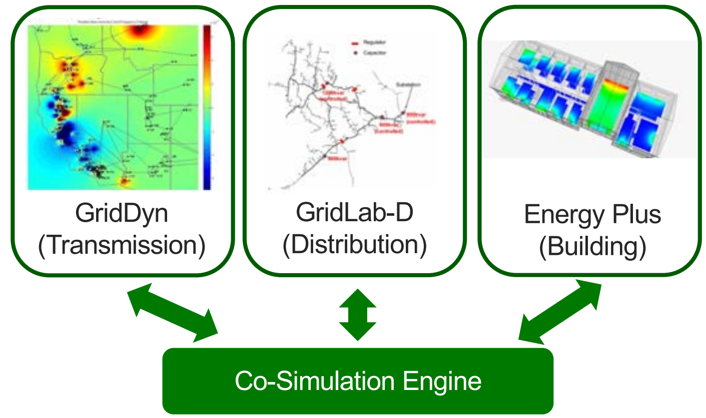
Broadly Two Types of Co-Simulation Coupling

Fully Integrated (the Modelica approach)



- All models needs to be developed in the Modelica-compatible tools
- Simulated in one solver; data is tightly coupled through library function calls
- Require broad knowledge and extensive experience

Fully Distributed (the HELICS approach)



- Glues various domain-software to simulate a complex system
- Solved separately; the co-simulation software handles the stepping and data exchange
- The user needs to design the interfacing algorithms to guarantee meaningful co-simulation results

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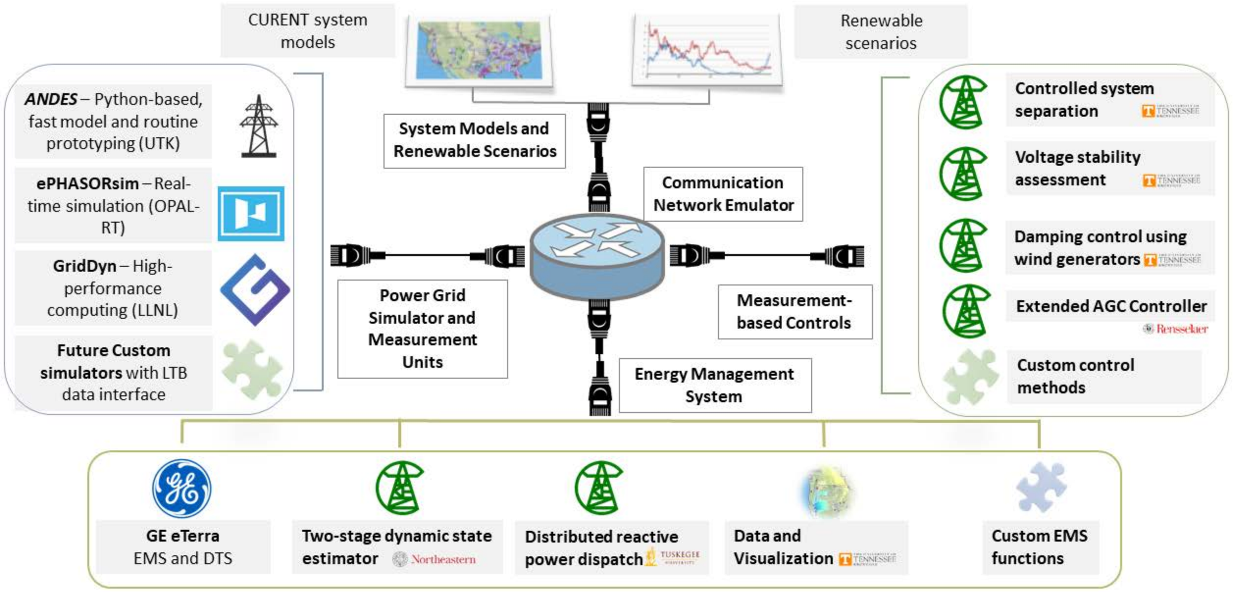
The Decoupled Architecture of LTB Co-Simulation

Our Hybrid Approach: The Decoupled Architecture



- Power system components are modeled in simulators *(we integrate models)*
- EMS and control modules are decoupled from the simulator through data streaming *(we decouple wide-area functions)*
- The simulator is responsible for stepping at the wall-clock speed *(also known as real-time)*
- Modules can be developed independently and run simultaneously
- Existing code or tools can be integrated and become interoperable

Design Considerations

- Interoperability
  - Modular architecture
  - Quick integration of new controls and algorithms
  - Easy to swap modules (simulators, EMS and controls)
- Measurement-based control integrations
  - Simulate PMU sampling and streaming
  - Convenient interfaces for measurement-based control algorithms
  - Human-in-the-loop control from the visualization front-end
- Large-scale model complexity
  - Reduced models for WECC, EI and ERCOT systems
  - 1000-bus North America power grid model with dynamics and HVDC
  - Verified models with real measurement data

LTB Grid Simulation Engines

Research and Prototyping

ANDES

- Built-in model library
- Fully open-source
- Fast prototyping of models and routines
- Python flexibilities

Lawrence Livermore National Laboratory

GRIDDYN

- Flexible modeling supports (Modelica and control blocks)
- Fully open-source
- High-performance numerical library
- Written in C++

Commercial Tool

OPAL-RT

ePHASORSim

- Real-time simulation capability
- Modelica support
- Python interfaces
- I/Os for hardware-in-the-loop control

ANDES (ANother Dynamic Energy System) simulator

- Application Background:
  - Large-scale power system simulations
  - Fast prototyping with built-in routine and device models
  - Highly customizable research tool
- Available Functions:
  - Power Flow for AC/DC hybrid system (Newton)
  - Time Domain Integration (Implicit Euler and Trapezoidal)
  - Eigenvalue Analysis
  - Plotting tools and data streaming interface
  - User-defined model translator
- Available Models:
  - Two generator models, two turbine governor models, three exciter models, two stabilizer models, Type III and Type IV wind turbine, current-source and voltage-source VSC models
- Extendibility:
  - Easy extension since it is Python based

Supported Data Formats:

- PSS/E raw and dyr
- MATPOWER
- DOME

Supported CURENT LTB Systems:

- NPCC 39-, 68- and 140-bus systems
- WECC (with 50% wind)
- EI (with 50% wind)
- ERCOT (with 50% wind)

Open-Source Distribution:

https://github.com/CURENT/ANDES

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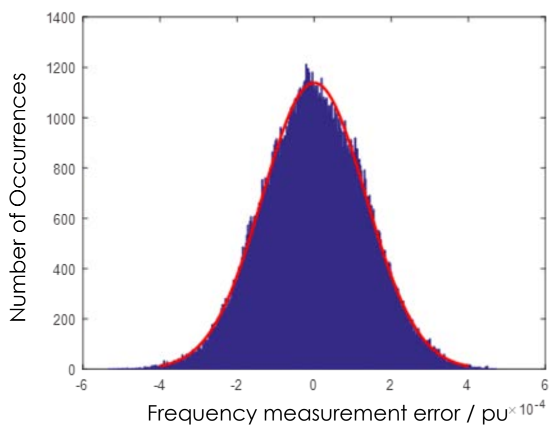
PMU Simulator Module (MiniPMU)

MiniPMU models generate measurement data from simulation data

1. Starts with a delay model

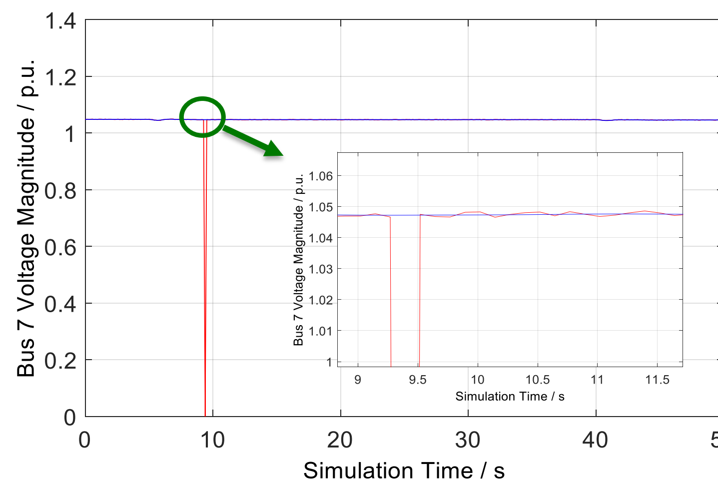
$$\begin{aligned}\dot{v}_m &= (V - v_m)/T_m \\ \dot{\theta}_m &= (\theta - \theta_m)/T_\theta\end{aligned}$$

2. Embeds measurement noises (Gaussian distribution)



3. Considers loss of data at a fixed probability (for example, 1/100)

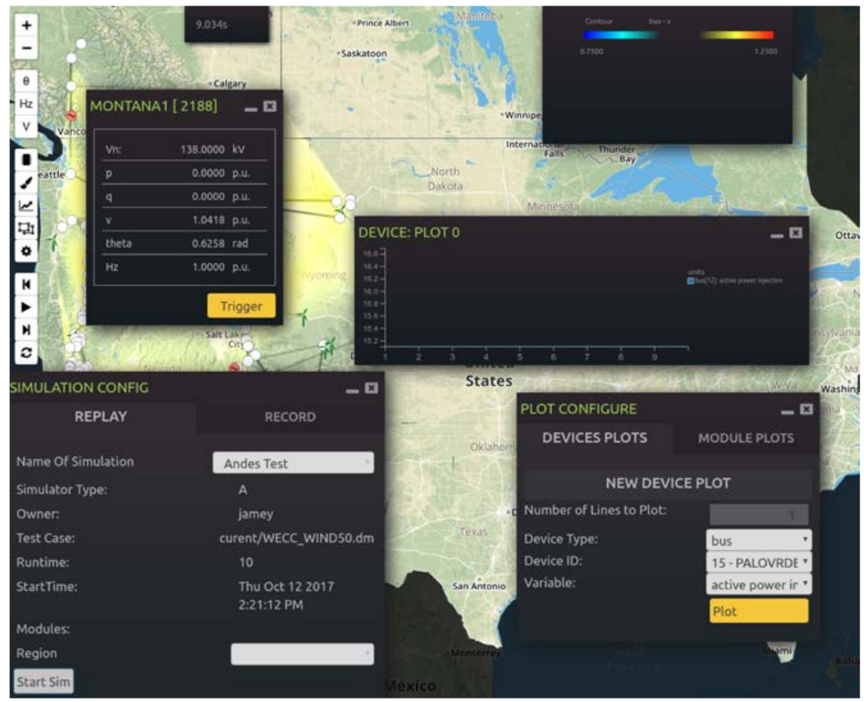
4. Sends the measurement data along with the accurate data



Visualization: LTBWeb

LTBWeb provides a web-based platform for visualization, comparing results, and interacting with the LTB system.

- For power system researchers
  - Run customized simulations from their own computers and stream data to the visualization platform.
  - Build energy management and control modules and use plots and contour maps for control visualization.
  - View simulations side-by-side to enable quick and easy visual comparisons.
  - Interact with live simulations such as trigger faults and opening lines.



User interface of the LTB visualization platform

Data Streaming Channels

- Modular Architecture Enabled by Data Streaming
- Case 1: DiME
  - Distributed Messaging Environment (DiME) for passing data between asynchronous, heterogeneous modules
  - Rapid point-to-point data streaming for fast prototyping
- Case 2: LTBNet
  - Network emulator based LTBNet for modeling communication network details
  - Standard IP-based streaming over detailed communication network

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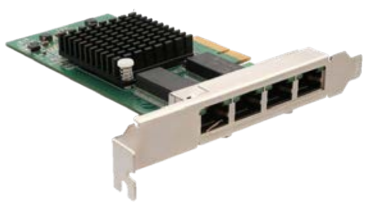
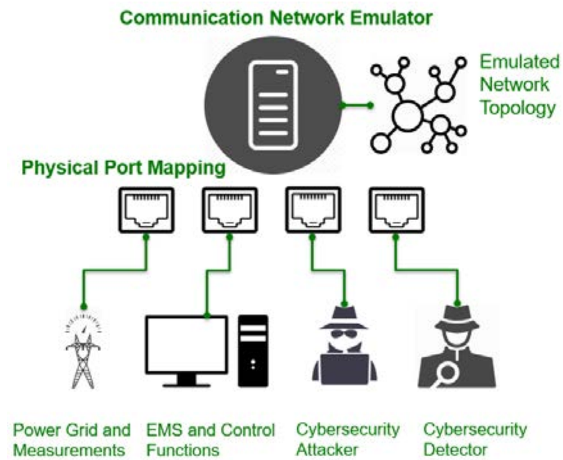
Network Emulator and Data Streaming Networks (1)

- Communication Network Emulation Hardware and Software Set up
  - Based on generic hardware + open-source software
    - Expendable to 12 physical network ports
    - Test shows the total bandwidth is about 50 Gb/s (depends on the CPU)

Dell Desktop Tower



Quad-Port Network Interface Card



Example for studying cybersecurity using network emulation

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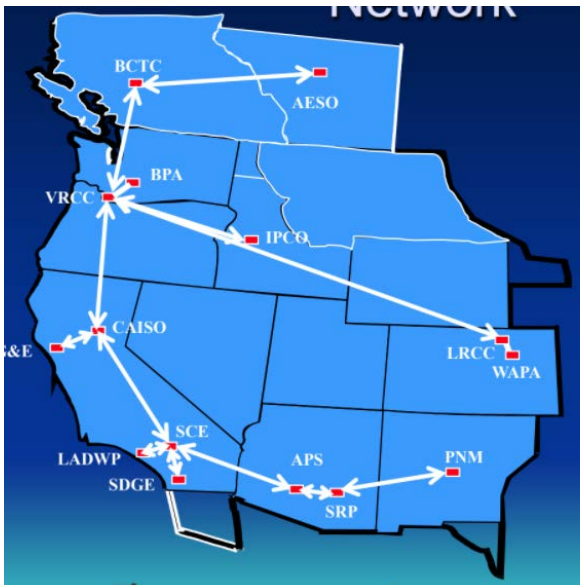
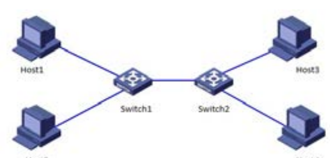
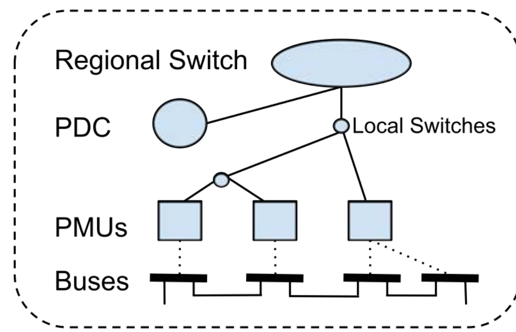
Network Emulator and Data Streaming Networks (2)

- Proposed Communication Network Topology in WECC
  - Define the data streaming topology in WECC based on a Quanta-Technology report
  - Developed the tool *LTBNet* which populated the communication network based on the defined topology from configuration files



- LTBNet creates the PMU Data Streaming Network





Network topology of regional PMU data streaming

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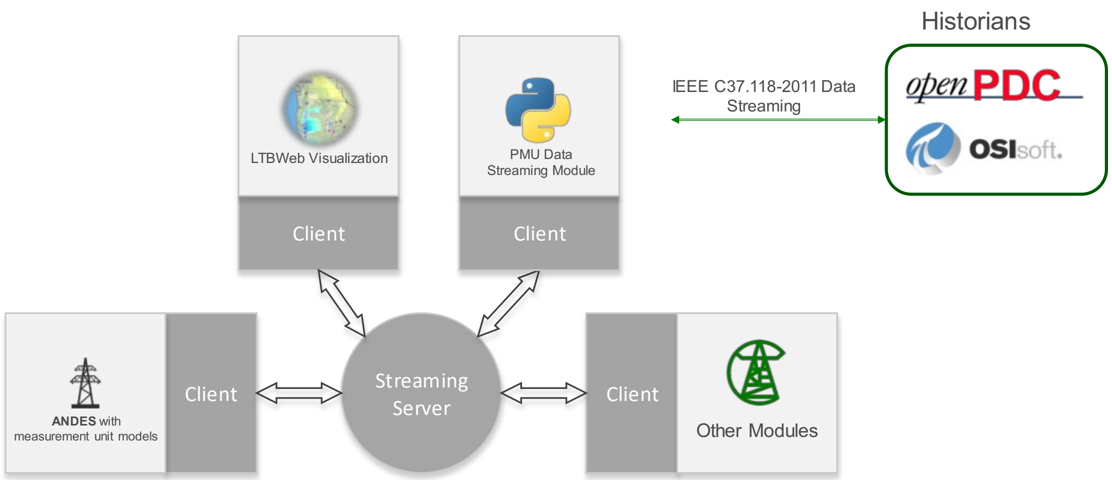
Distributed Messaging Environment (DiME)

LTB **Di**stributed **M**ATLAB **E**nvironment (DiME) supports the decoupled architecture and streams data amongst all the modules

- One Python-based, transparent streaming server
- Supports unlimited MATLAB, Python, or C++ clients
- Developers can import DiME API easily and gain streaming capability in function modules



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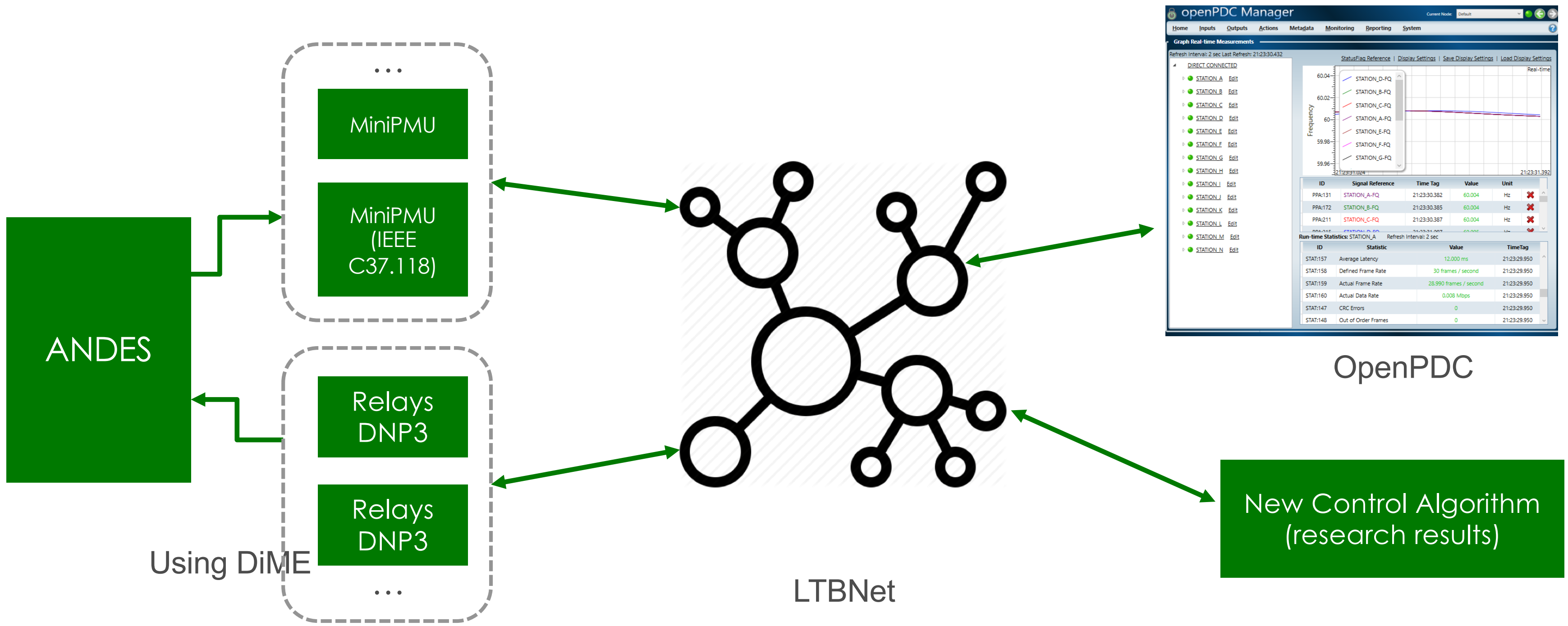
Bringing Power and Communication Together

- Represent the sensing and actuation systems between the physical system (simulator) and the cyber systems (EMS and control system)



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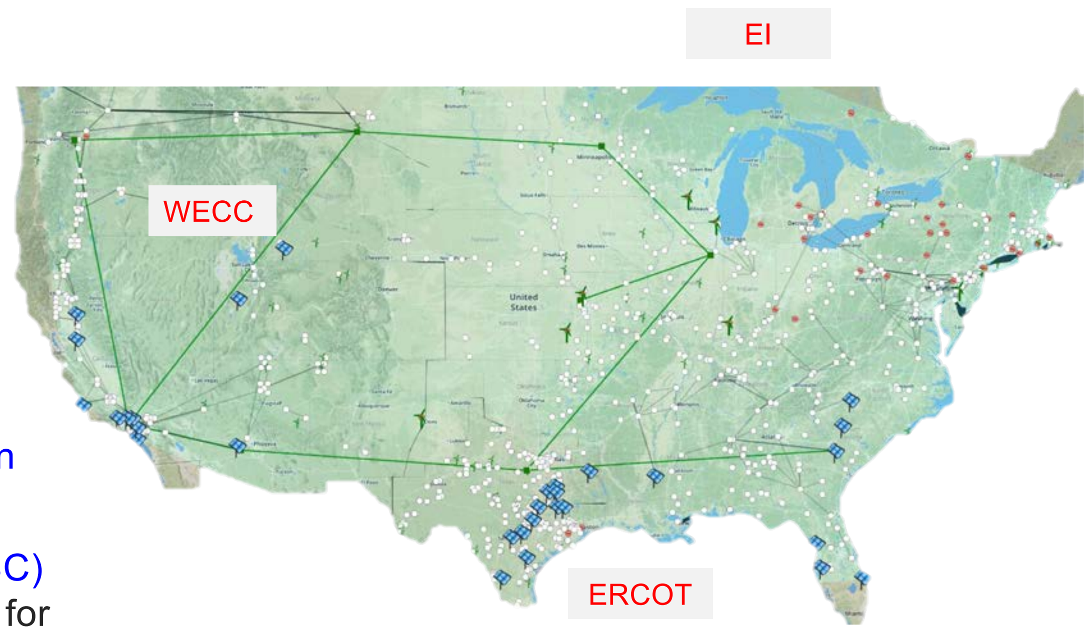
LTB Test Systems and Scenarios

- The goal is to integrate utility-scale renewable generation into the North American system by replacing or retiring conventional generations.

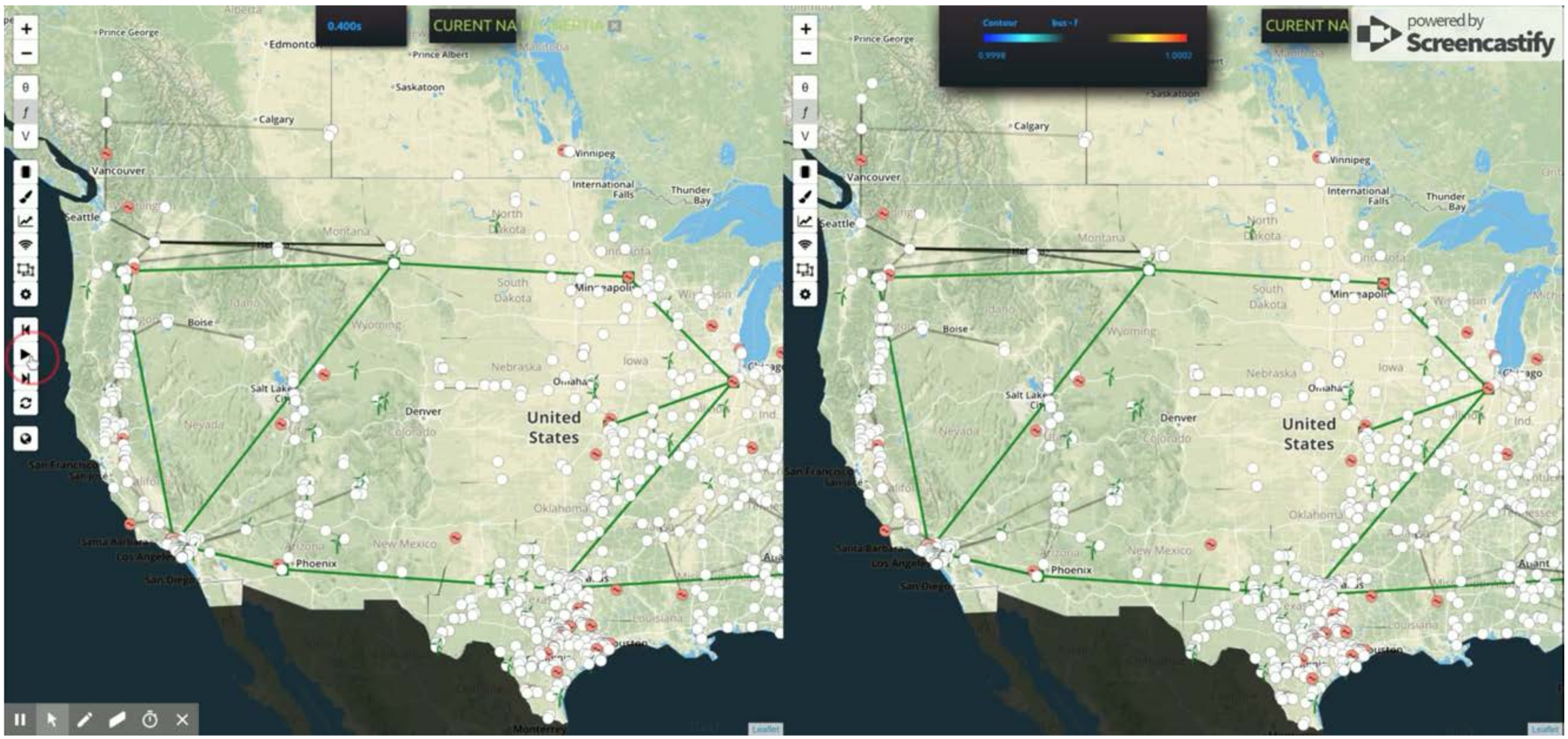
- Key achievements:
  - Created a 1,000-bus *CURENT* system, including WECC, EI and ERCOT
  - Reduced EI with detailed NPCC
  - 50% wind penetration in each interconnection
  - 30% PV penetration (on-going work)
  - A nine-terminal voltage source converter (VSC) based HVDC overlay is added to the system for wide-area power transfer.



CURENT 1,000-bus test system with 50% wind and 30% PV penetration and a nine-terminal VSC HVDC

Demo: WECC Frequency Control with Wind Inertia

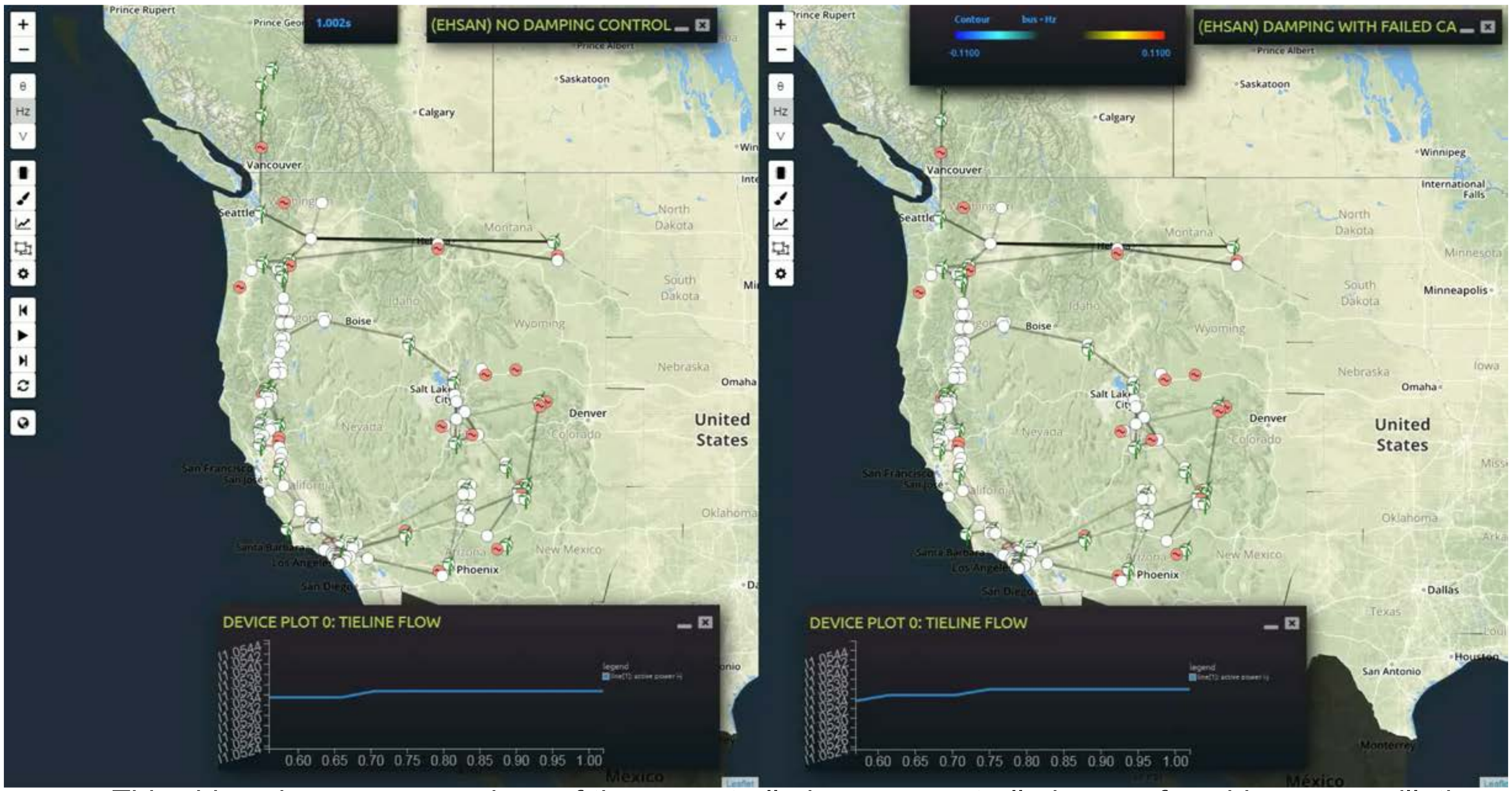
Uncontrolled Controlled



This video shows a comparison of the uncontrolled versus controlled cases for wide-area frequency control. The frequency in the uncontrolled case drops faster than the controlled case.

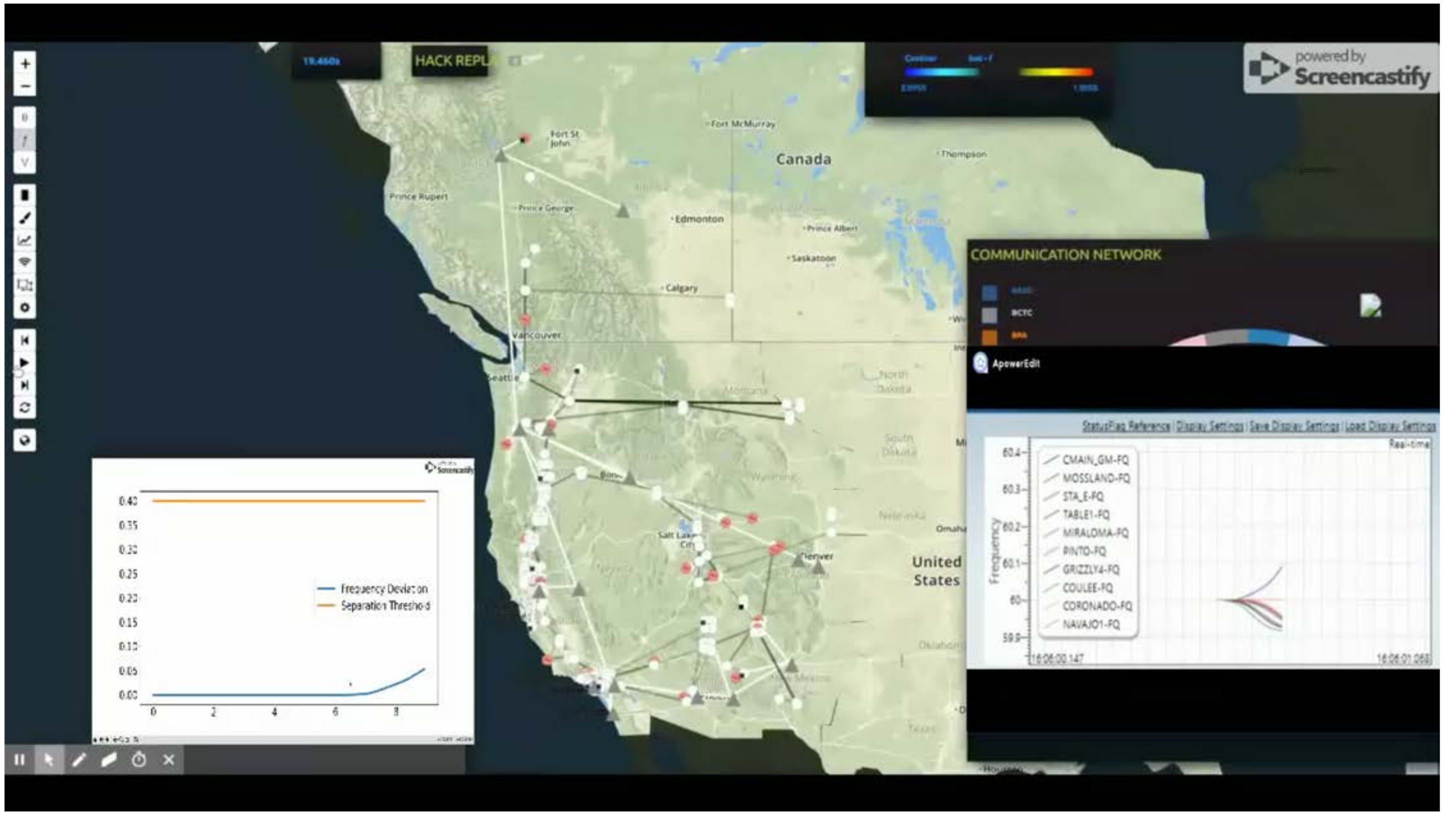
Demo: WECC Damping Control using Wind Generators

Uncontrolled | Controlled



This video shows a comparison of the uncontrolled versus controlled cases for wide-area oscillation damping using wind generators. The oscillation damps out faster in the controlled case.

Demo: Cyber Attack – False Data Injection



This video shows a cyber attack using a false data attack (replay attack). The system separation takes place due to misinformation.

HTB Top-level Goals and Needs

- **System-level outcome**
  - Interconnected (reduced bus model) EI/WECC/ERCOT with 80% renewable, featuring HVDC overlay and regional MTDC, fully-monitored transmission & some monitored loads, fully integrated closed-loop control on frequency, voltage, damping, and adaptive RES for improved transfer limit and reduced reserves
- **HTB**
  - Modeling/building: reduced models of each of the 3 interconnections with variable RES levels up to 80%
  - Control architecture: 3-layer traditional control with central control, regional control, and local control (also internal converter control).
  - Protection architecture: Local level protection.
  - Communication architecture: Ability to emulate power system communication
  - Event capability: black start with renewables, restart, normal operation, fault, scheduled/unscheduled change of loads/sources/lines
  - Operation: interactive, scenario setting, visualization
  - Needs from: 1) actuation – real-time capability/modes, Var sources, inertia source, HVDC transmission & flow control; 2) monitoring; 3) modeling/estimation, and 4) control

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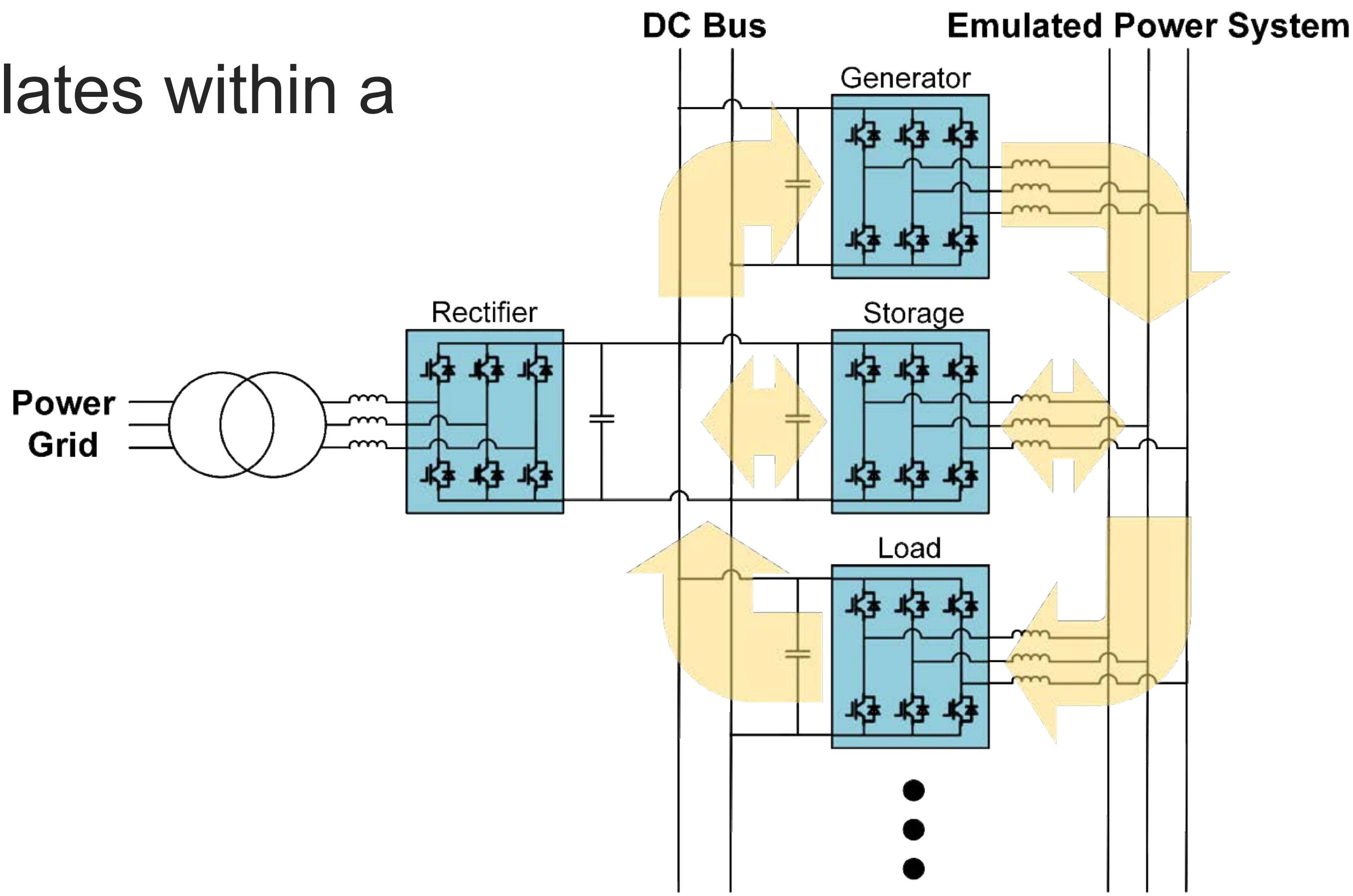
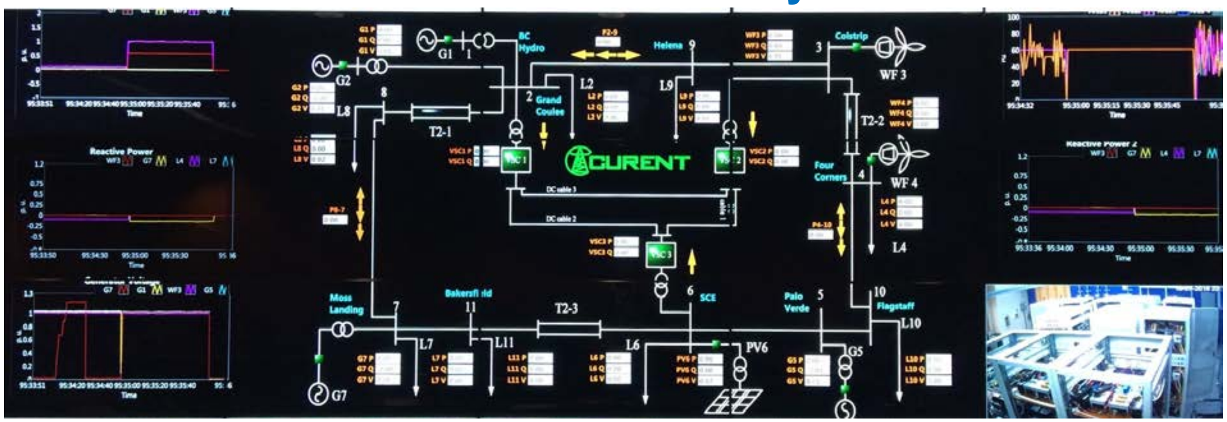
Hardware Testbed (HTB) Background

- Power circulates within a single area



Communication, Control, and Visualization（4 area）

Visualization Room Layout



Station 1 | Station 2 | Station 3 | Station 4

Central Controller | Computer 1 (Area 1) | Computer 2 (Area 2) | Computer 3 (RTDS) | Computer 4 (Area 3) | Computer 5 (HVDC) | Computer 6 (Area 4)

Control Center functions

<u>Area control center:</u>

- Control local area
- Independent from each other
- Dispatch transmission lines
- Implemented with *AGC*, *local state estimation*, *voltage monitoring*, etc.

<u>Central controller:</u>

- Only for automatic scenario sequencing and demonstration
- Future system level testing

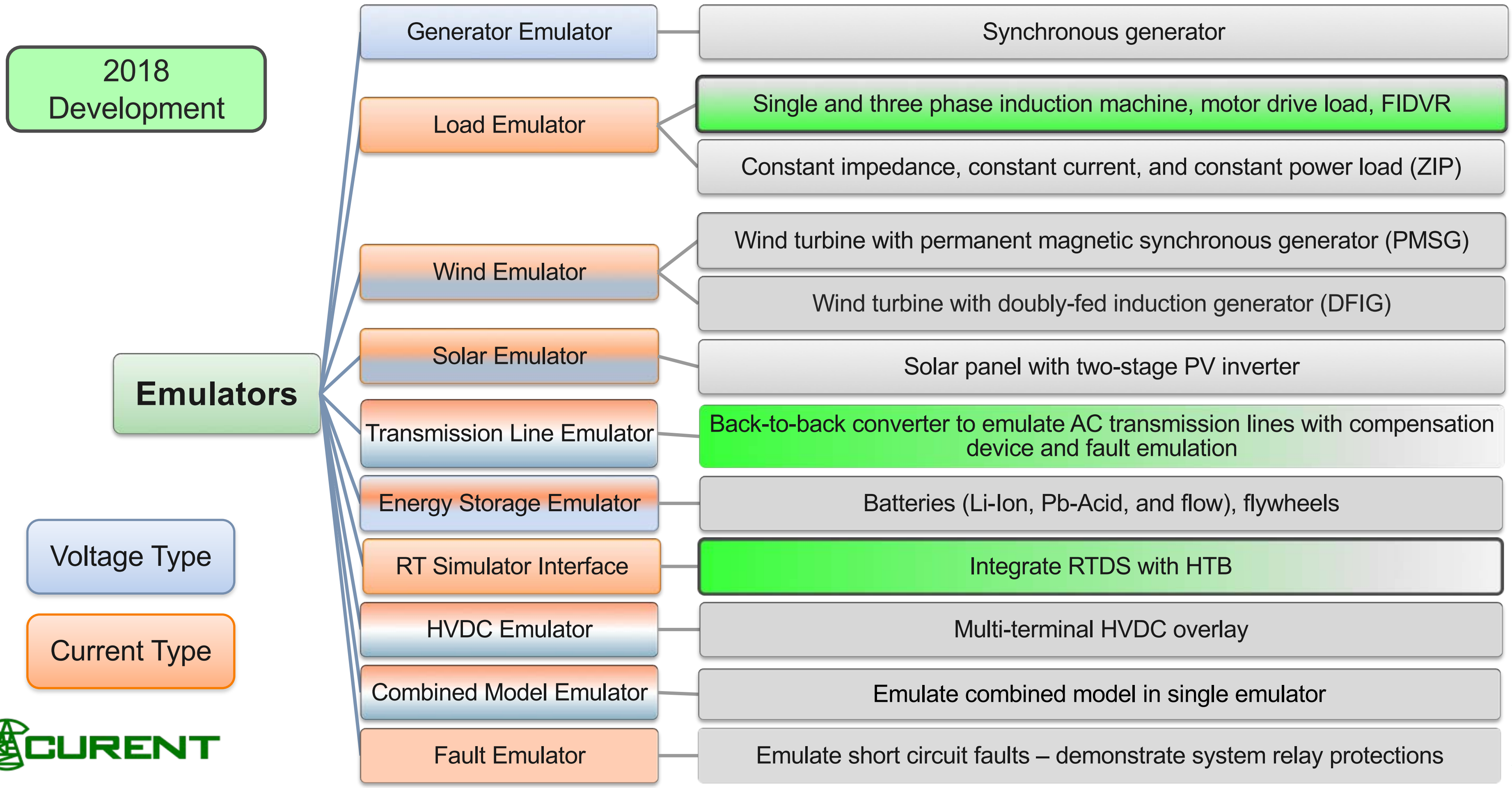
<u>Visualization computer:</u>

- Only for display of system information on the video wall

Hardware Test-bed Advantages

- Broad time scales in one system - microseconds for power electronics to miliseconds and seconds for power system event.
- Integrate real-time communication, protection, control, and power (and cyber security).
- Multiple power electronic converters (for wind and solar and energy storage) with separate controls.
- Capable of testing actual communication and measurements.
- A useful bridge from pure simulation to real power system application.

Components in Areas and Transmission Systems



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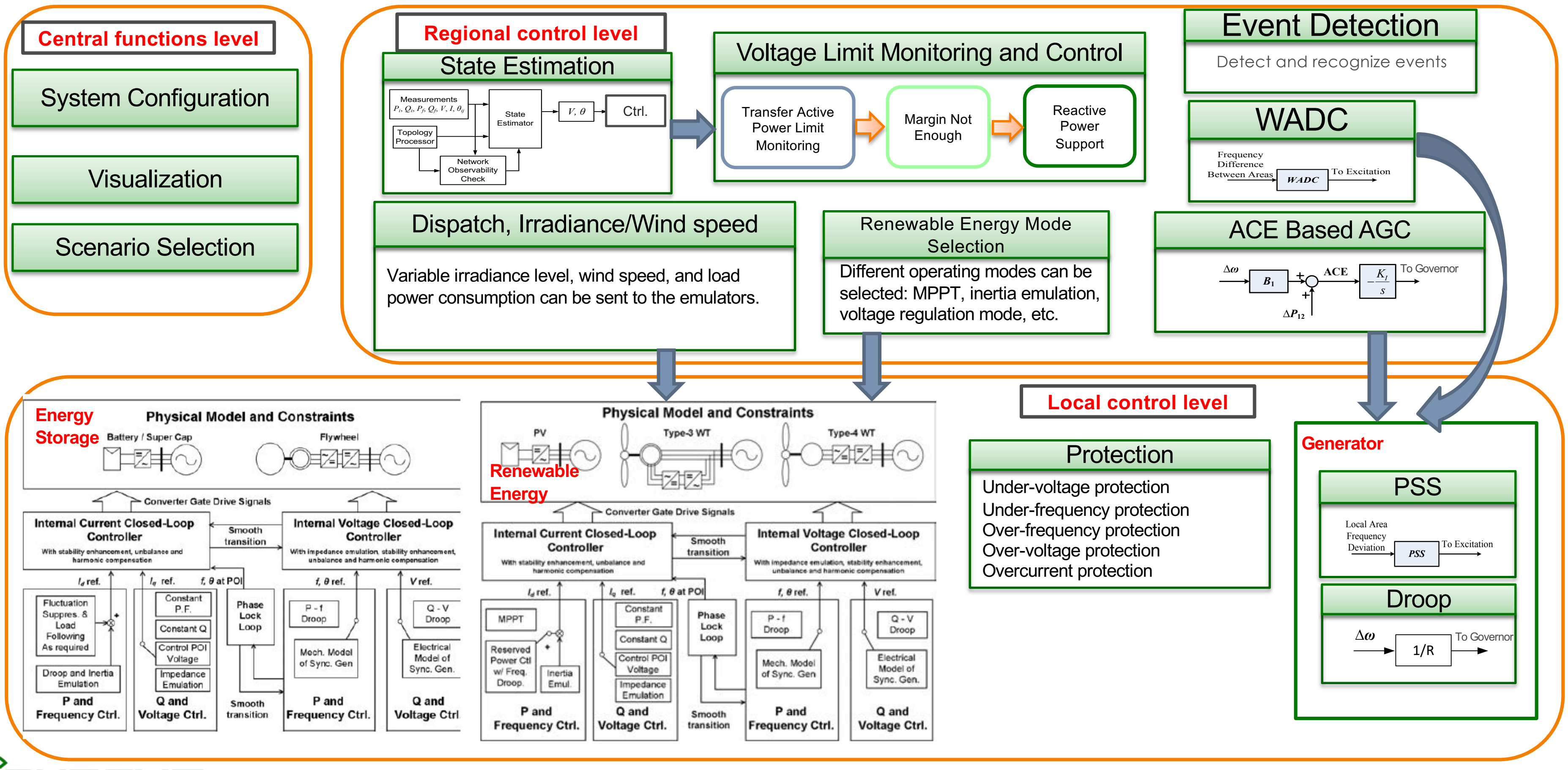
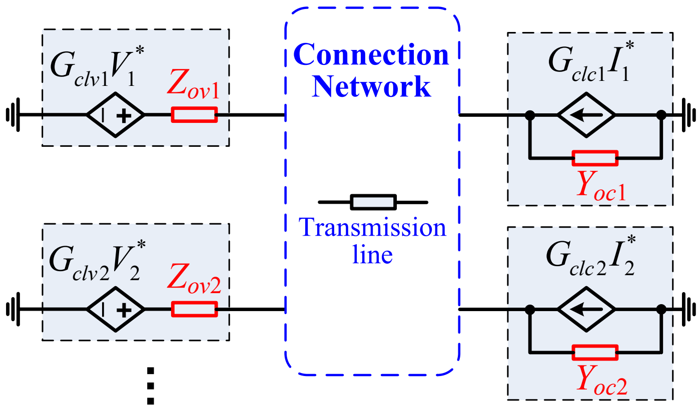
Multiple Simultaneous Control Functions



Mitigation of Unstable Harmonic Resonances in HTB

HTB: converter-based power system

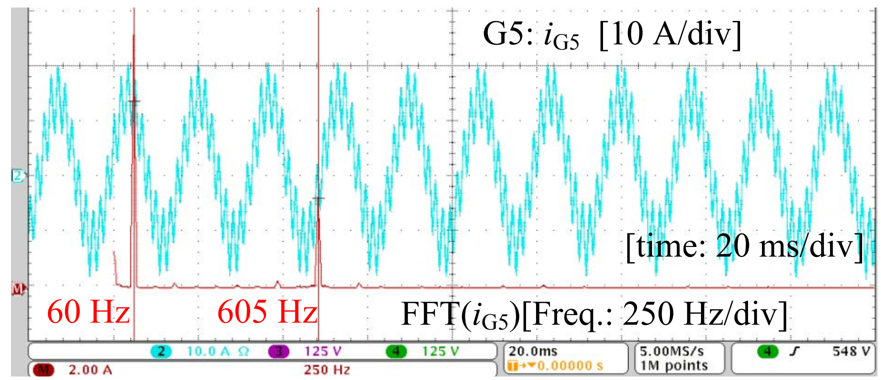


Voltage-controlled converters
- Generators
- Renewables in voltage-control mode
- Non-ideal: non-passive output impedances

Current-controlled converters
- Loads
- Renewables in current-control mode
- HVDC
- Energy storage
- Non-ideal: non-passive output admittances

Unstable harmonic resonances

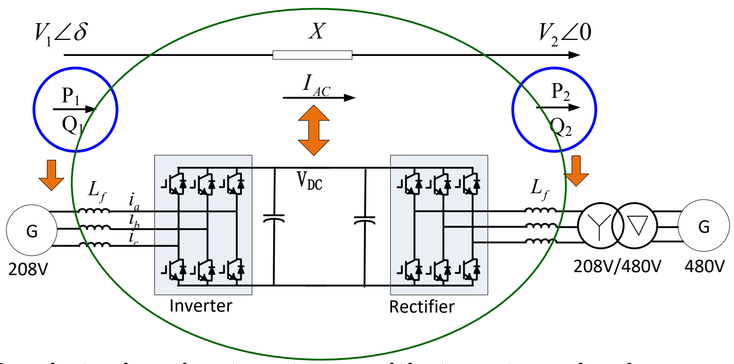
Unstable harmonic resonances



Approach to Mitigation

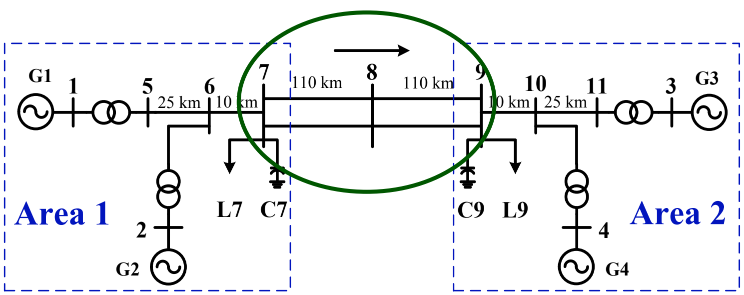
Adjusting converter controller parameters:
- Trade-off
- Increase the passivity of the converter impedances or admittances
- Reduce control bandwidth of converters (still sufficient for emulation of power system)

AC or DC Transmission Line Emulator



Back-to-back structure with two terminals

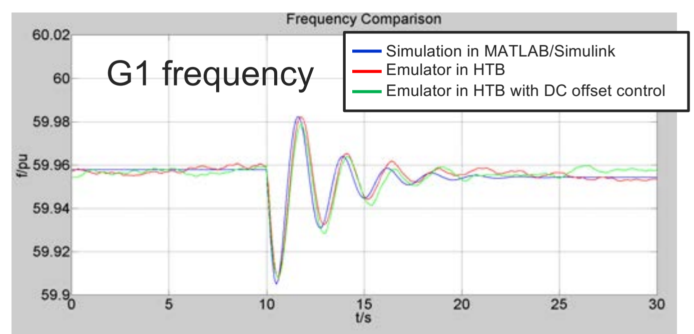
Line 7-9



Transmission Line Emulator Attributes

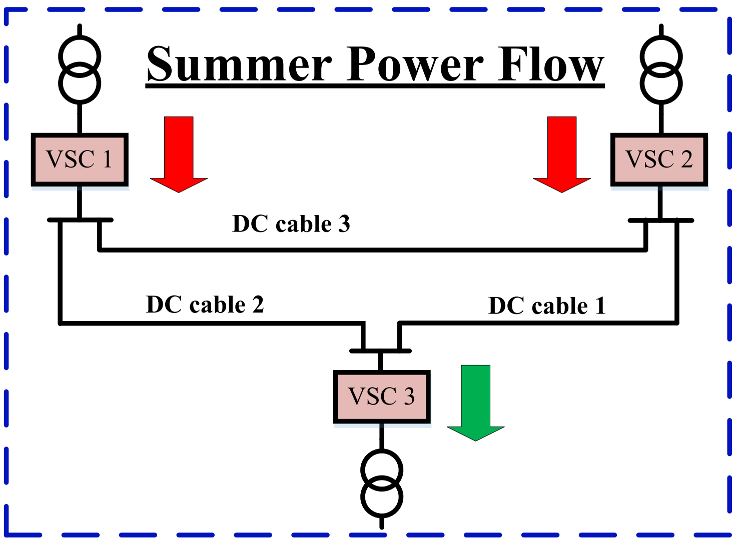
- Vary the line length (impedance) for different scenarios
- Short circuit or open line faults
- Reclosing emulation
- Emulate multiple parallel lines
- Emulate FACTS applications such as CVSR

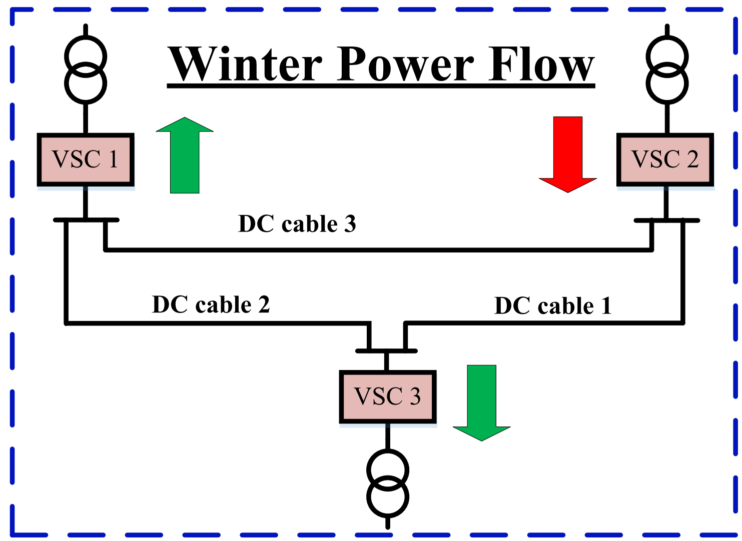
Comparison between the emulator and simulation with line impedance change (line drop)



Voltage Source Converter (VSC)-Based Multi-Terminal HVDC Overlay

- DC overlaying an AC system is suitable for transferring remote renewable energy to load centers
- **Less converter numbers and potential cost benefit** of multi-terminal configuration compared to building multiple point-to-point transmission lines
- **Easy power flow reverse, smaller footprint** by using voltage source converter (VSC)
- **DC power flow controller** and **DC fault protection** need to be addressed





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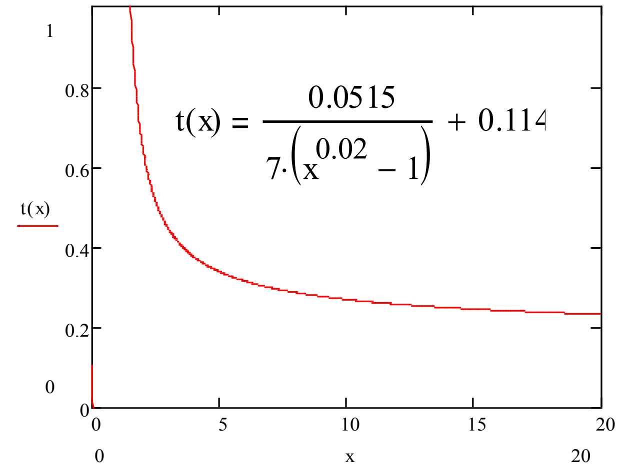
System Protection

- Inverter DSP's have been programmed to have their own protection based on system model parameters
- Parameters were chosen by WECC protection standards
- Automatic actions such as load shedding and generator trips can be taken
- Loads have under-voltage and under-frequency protection
- Generators have over-current, under-frequency, and over-frequency protection

Generator Overcurrent Protection Curve



Load under-voltage

Voltage Set-Point, p.u	Tripping time, s	Load Dropped, %
0.9	3.5	5
0.92	5	5
0.92	8	5

Load under-frequency

Frequency Set-Point, Hz	Tripping time, Cycle	Load Dropped, %
59.1	14	5.3
58.9	14	5.9
58.7	14	6.5
58.5	14	6.7
58.3	14	6.7

Generator under and over frequency protection

Under-frequency	Over-frequency	Tripping time
59.4	60.6	3 minutes
58.4	61.6	30 seconds
57.8	-	7.5 seconds
57.3	-	0.75 seconds
57	61.7	instantaneous

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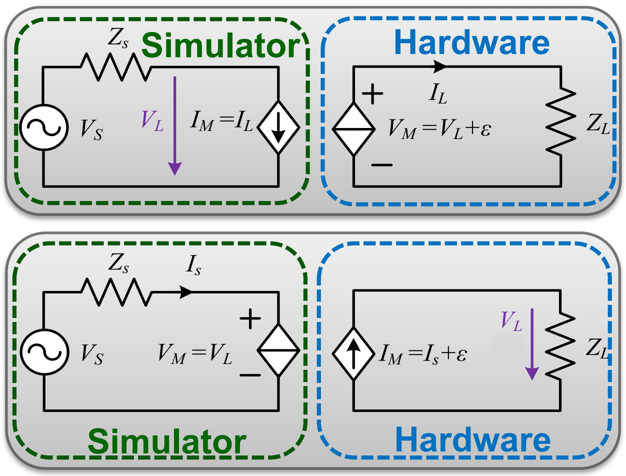
RTDS Interface with HTB

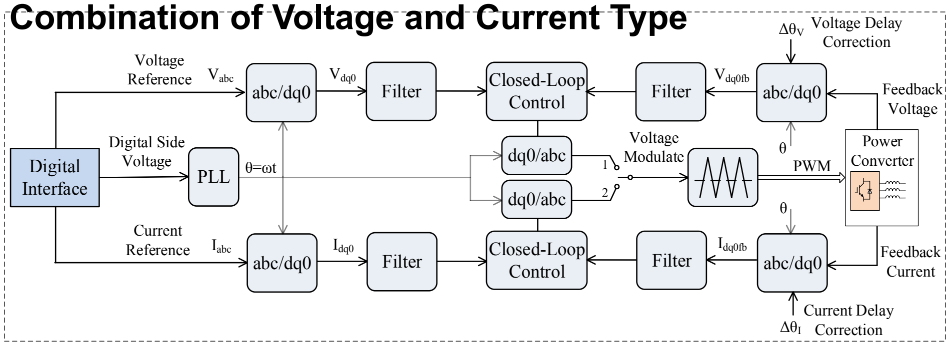
Interface Algorithms:

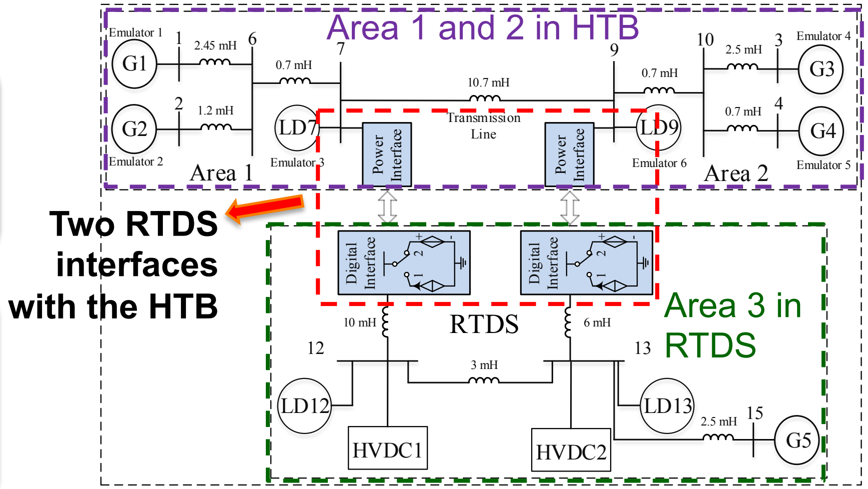
Voltage Type

Current Type



Combination of Voltage and Current Type





RTDS Interface Attributes

- Expand HTB to more than 40 buses
- Unique system that has both control and power hardware interface

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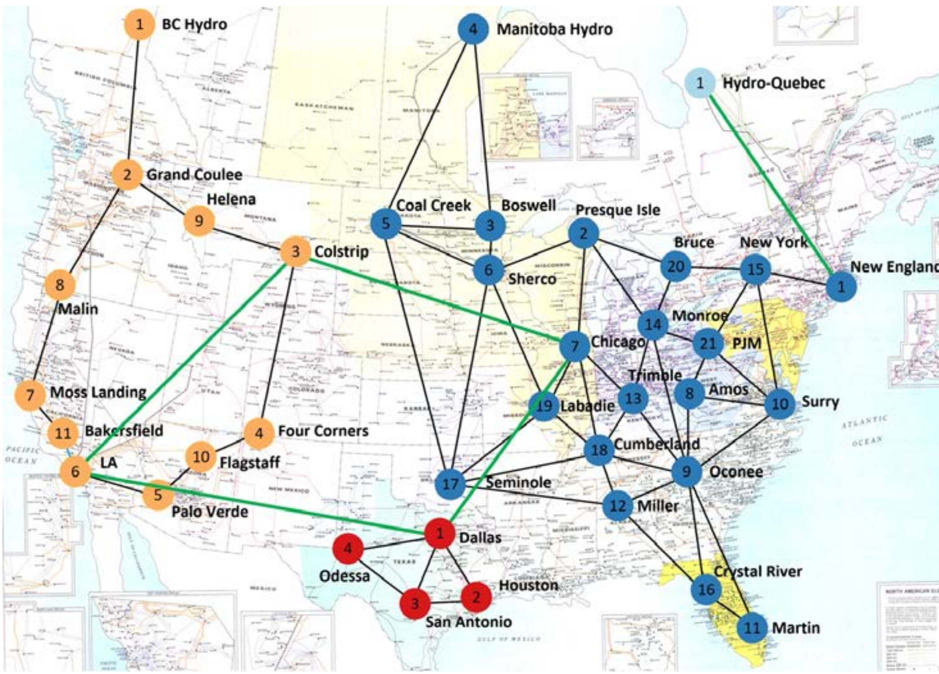
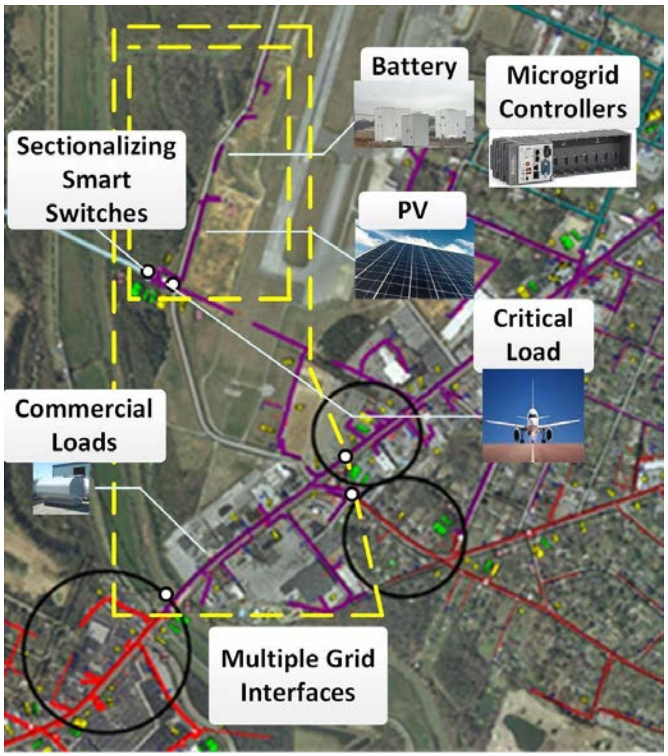
North American Grid with HVDC Overlay



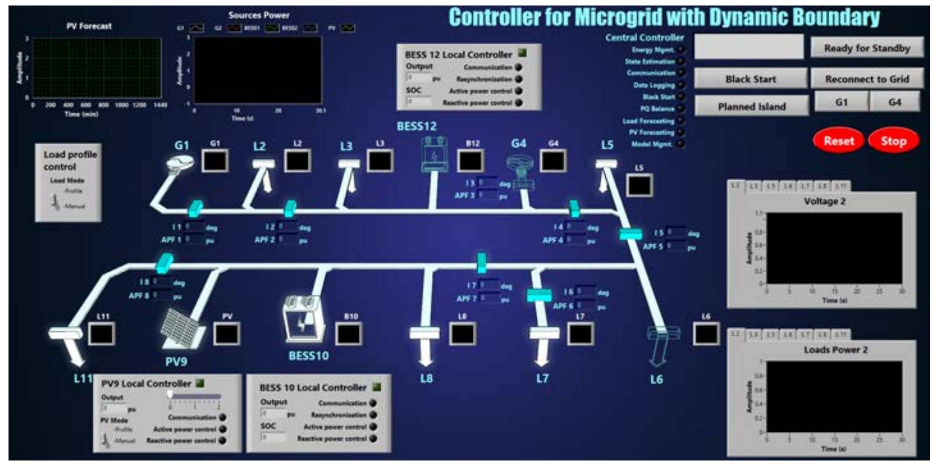
North American Grid with WECC, EI, and ERCOT systems connected via multi-terminal HVDC overlay, and high penetration of renewable energy sources

HTB Microgrid Controller Testing

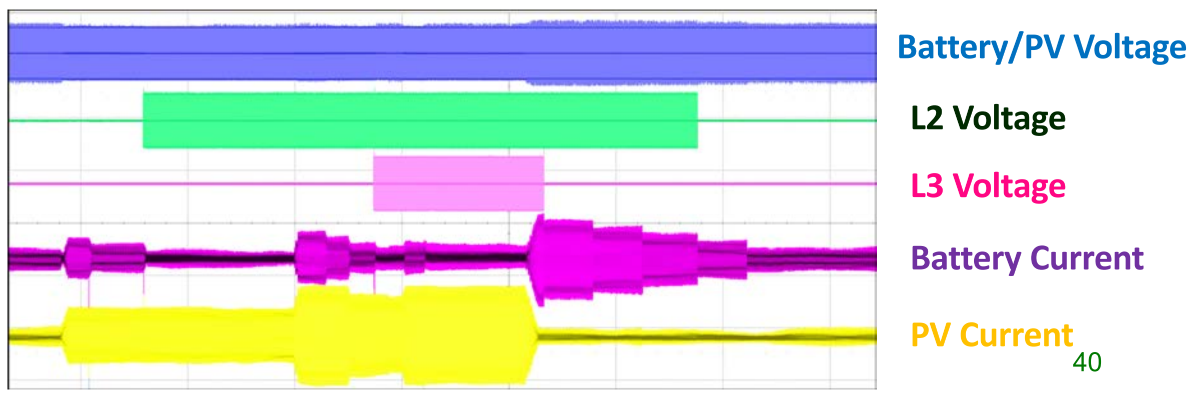
Microgrid with Dynamic Boundary by Sectionalizing Smart Switches



Controller Interface for HTB Tests



Oscilloscope Measurements of Boundary Change Tests



Scenario Development and Resilience

- What sort of scenarios should be studied in the future?
  - New weather related scenarios – heat spells, low wind scenarios, and so on.
  - Extreme events for resilience.
- Resilience vs. traditional security and reliability
  - Time variability – parameters describing events, and especially system recovery
  - Control actions should be explicitly modeled - effects of interventions
  - Economics – today, reliability is paid for by the customer, while resilience payments may include society / tax-payer because of its social impact.

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Resilience: Why now?

- Many countries throughout the world face an ongoing challenge of protecting their critical infrastructure from significant damage caused by extreme weather events, and actual or postulated physical- and cyber-attacks.
- Many of these natural hazards and threats from outside actors continue to increase in both frequency and intensity…

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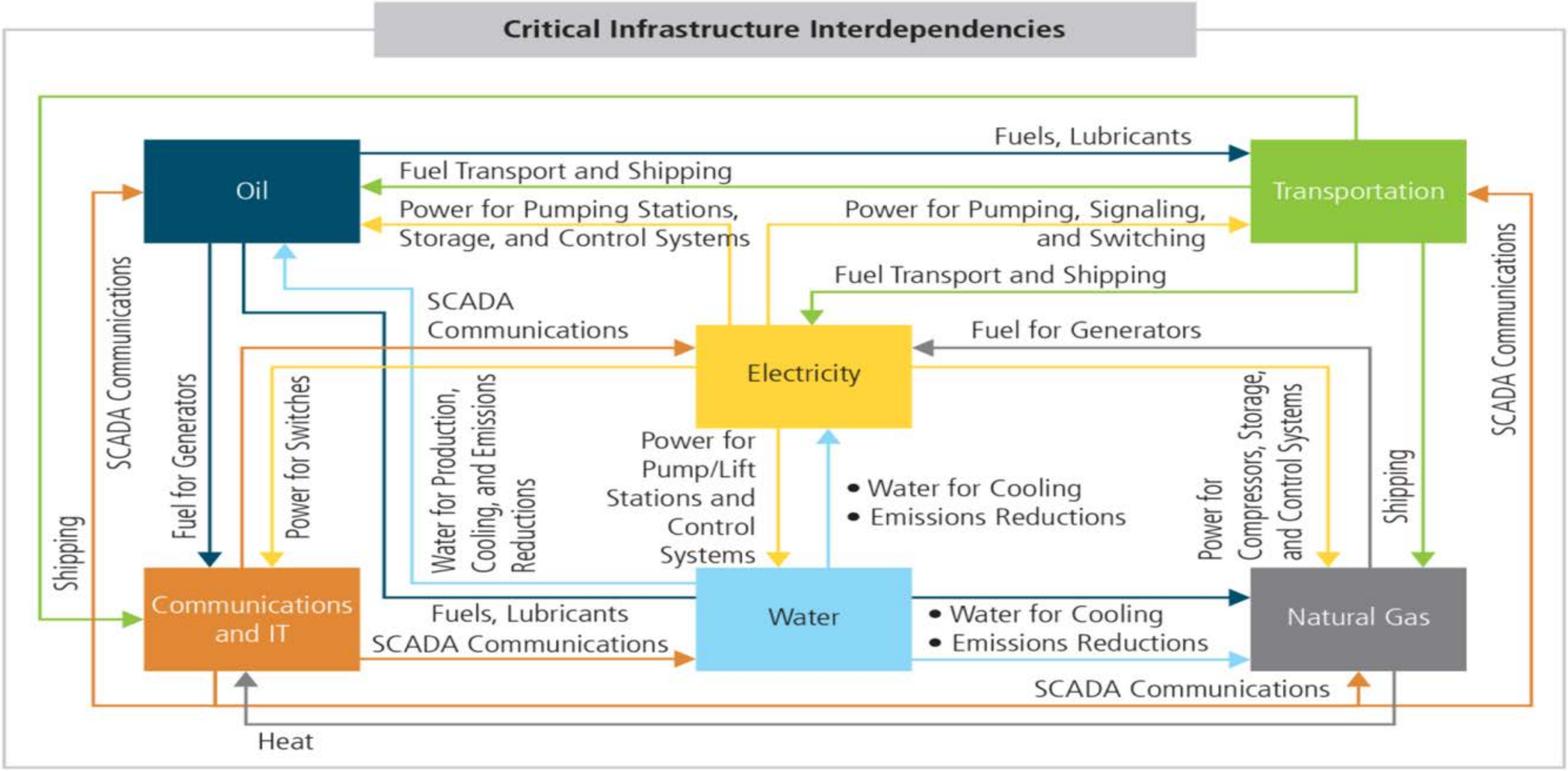
Interdependencies



Argonne 2016, DOE 2017 (QER)

Resilience Definitions – Conceptual

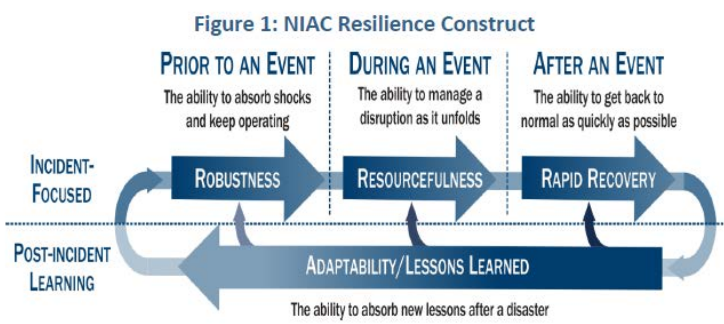
"The capacity of a system to absorb disturbance and reorganize so as to retain essentially the same function, structure, and feedbacks – to have the same identity" (Walker & Salt, 2012)

"The ability of an entity—e.g., asset, organization, community, region—to anticipate, resist, absorb, respond to, adapt to, and recover from a disturbance" (Carlson et al., 2012)

1.absorb, 2. reorganize, and 3. learn and adapt.

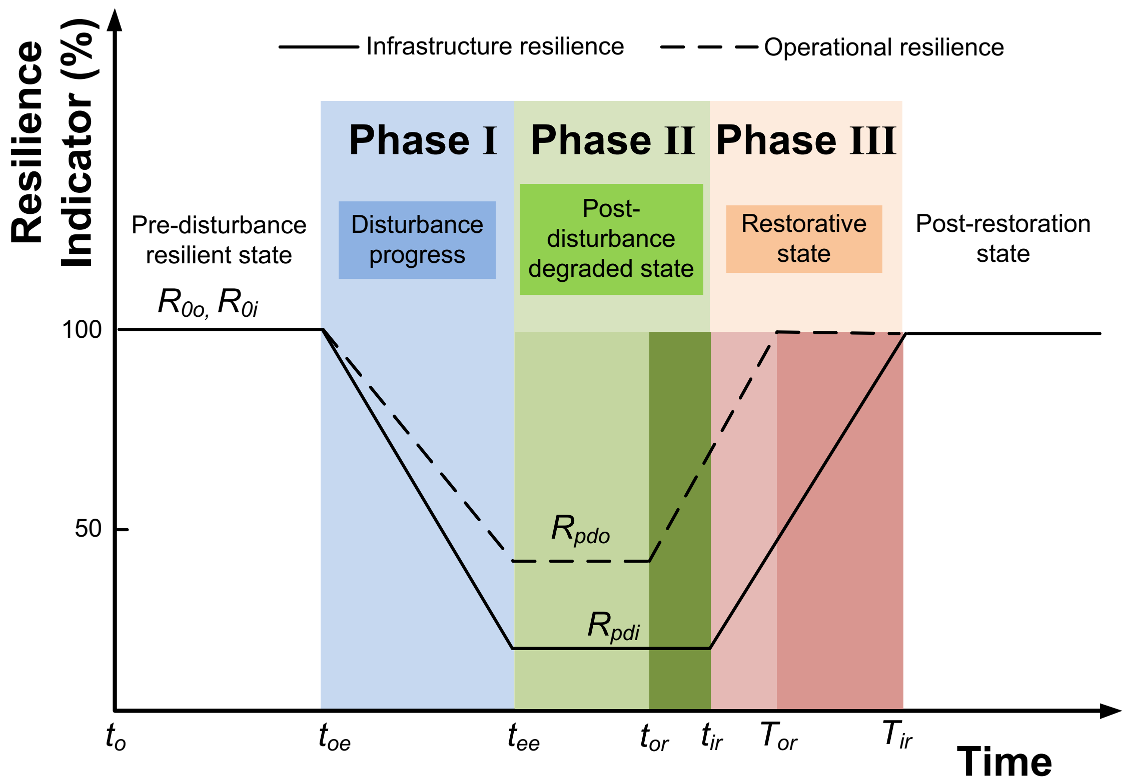
Definitions - Technical

The ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions. Resilience includes the ability to withstand and recover from deliberate attacks, accidents, or naturally occurring threats or incidents." US Presidential Policy Directive 2013.



National Infrastructure Advisory Council 2010

Definitions – Technical 2



The operational and infrastructure resilience trapezoids

Open Questions for Future Testbeds and Modeling

- Scenarios
  - Must be system specific but which events?
  - Can realistic models really be developed for extreme events?
- Multiple infrastructures
  - Should one model each infrastructure with some detail or only the interdependencies?
  - Which infrastructures need to be considered for the grid?
- New models
  - How to integrate models and interdependencies?
  - How to validate?

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pjm
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Traditional vs LTB Approaches for Testing Research

	Traditional Approach	*LTB Approach*
Prototyping	MATLAB/Simulink	Any programming language including MATLAB, Python, and C++
Data interfacing	Offline, manual data transfer between different simulators	Online data streaming between heterogeneous modules
Communication Network	None or manual	Built-in LTBNet
Closed-loop Testing	Manual simulator-controller loop	Real-time closed loop with cyber-physical models integrated
Systematic Testing	None or manual	Ready-to-use modules