Grid Emulation through Power Electronics Hardware Testbed

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The University of Tennessee

Seminar
IEEE East Tennessee Section

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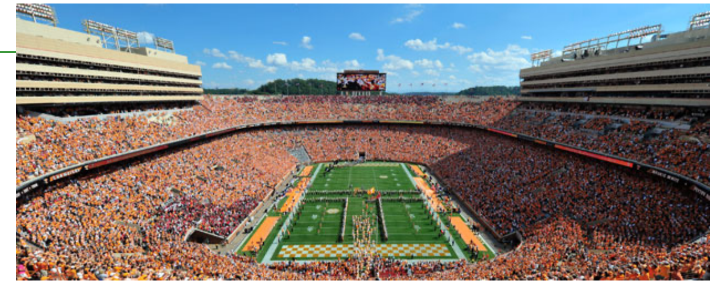
About UTK Electrical Engineering



- **UTK EECS Department (web.eecs.utk.edu)**
  ~50 faculty ~250 Graduate Students ~900 Undergraduates
- **CURENT** – NSF/DOE-sponsored Engineering Research Center on power transmission
- **PoTenntial** – Graduate research traineeship in wide bandgap power electronics
- **Oak Ridge National Laboratory**
  - Advanced Power Electronics and Electric Machines
  - Utility and Building Power System Applications

curent.utk.edu **PoTenntial.eecs.utk.edu** **ornl.gov**

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

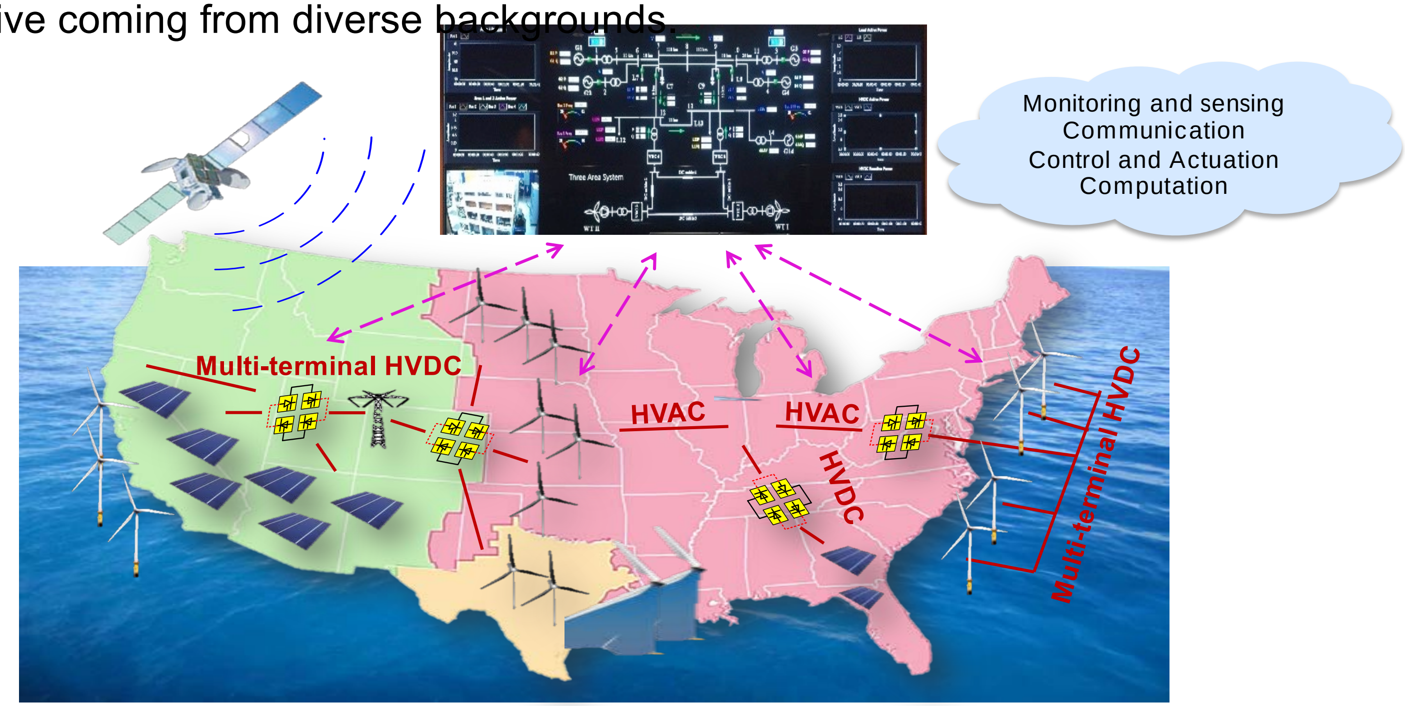
POTENNTIAL

OAK RIDGE National Laboratory

CURENT

CURENT Vision

- A nation-wide transmission grid that is fully monitored and dynamically controlled for high efficiency, high reliability, low cost, better accommodation of renewable sources, full utilization of storage, and responsive load.
- A new generation of electric power and energy systems engineering leaders with a global perspective coming from diverse backgrounds.



CURENT Members

Utilities RTOs/ISOs

Vendors

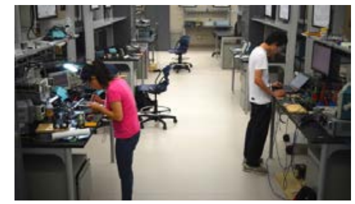
Research Consortia

UTK Power Electronics

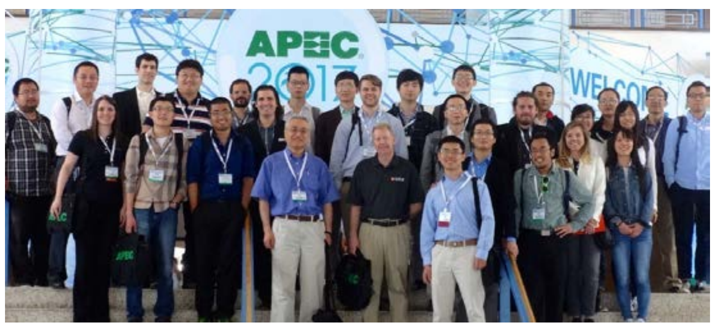
- Five full-time power electronics faculty
  - Daniel Costinett, Fred Wang, Leon Tolbert, Kevin Bai, Helen Cui






- 40 Graduate students in power electronics
- ~80 Graduate students in CURENT (Power Elec./Systems)
  - One of the largest graduate power programs in the US
- Close collaboration with Oak Ridge National Laboratory
- Focus on **hands-on**, **design-oriented** coursework and training

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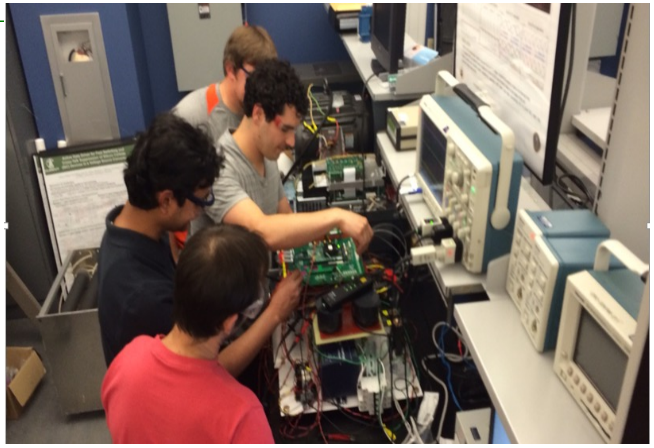
PoTENNTIAL WBG PE Graduate Traineeship

- DOE-funded traineeship in wide bandgap power electronics
- $2.9 Million, 6-year DOE sponsorship – one of only two awardees in the nation (Virginia Tech)
- Funds U.S. citizen graduate students (25 graduates and 10 current students in program)
- Hands-on coursework and research leveraging WBG
- Emphasizes internships with industry & national laboratories
- PoTENNtial.eecs.utk.edu

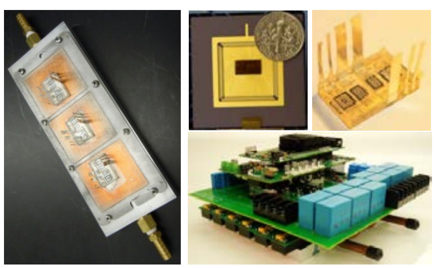


Power Electronics Facilities

- UTK, as part of the NSF-DOE Engineering Research Center CURENT, boasts one of the largest and best-equipped university power electronics laboratories in the nation.
- Multimillion-dollar state-of-the-art laboratory contains all electrical, mechanical, and thermal equipment and testing infrastructure necessary to characterize, model, design, construct, test, and control power electronics up to 1 MW and 40 kV.
- A new lab, opened in 2020 contains equipment for power module fabrication.

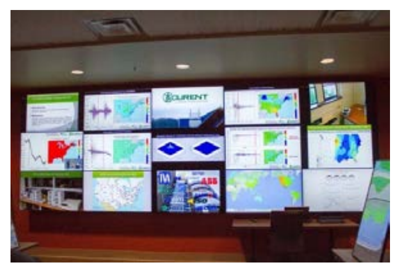
Low and Medium Power Lab

Grid Emulation Lab



Example Projects

Packaging Lab Equipment



Control and Visualization Lab

High Power Lab

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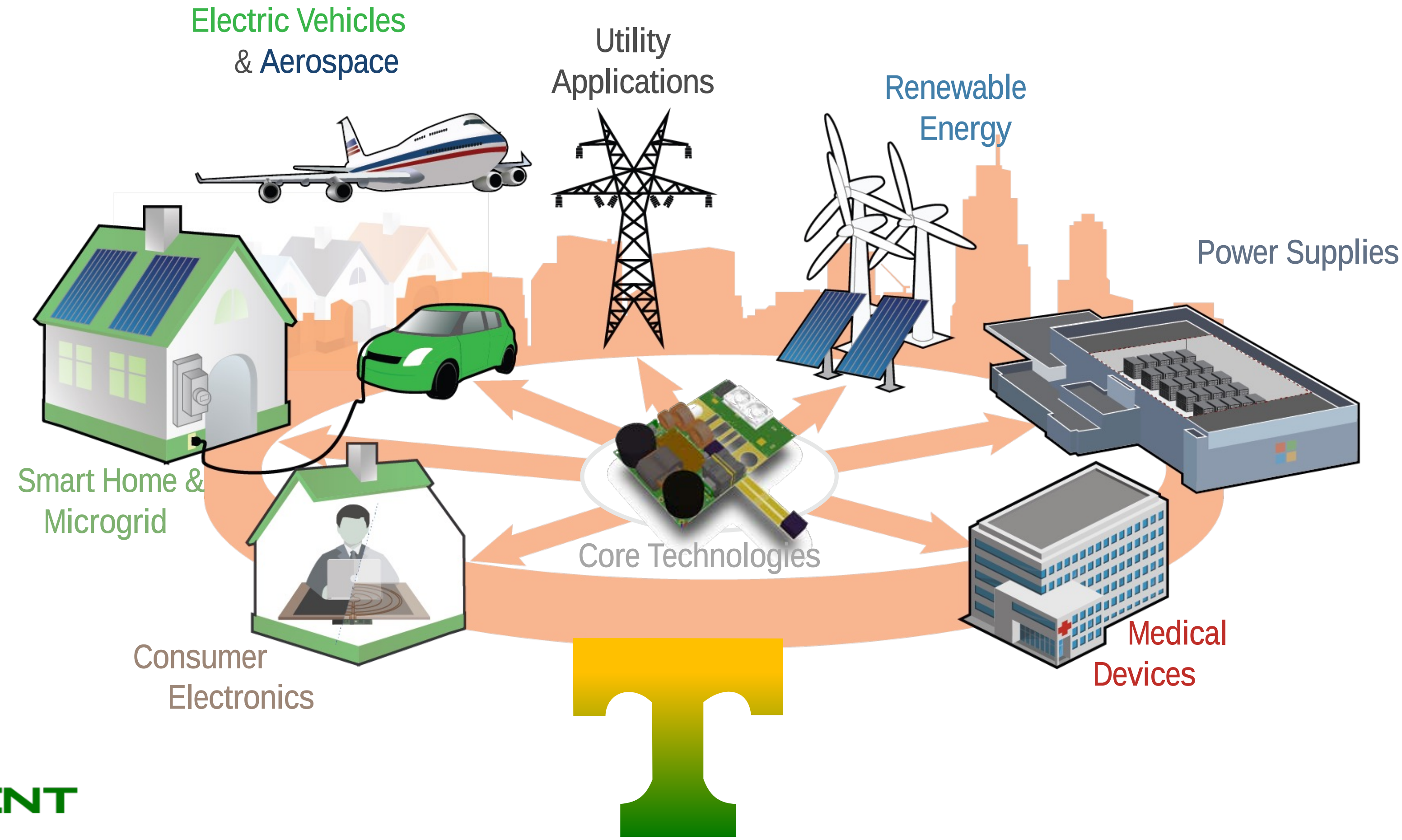
Power Electronics Research Applications



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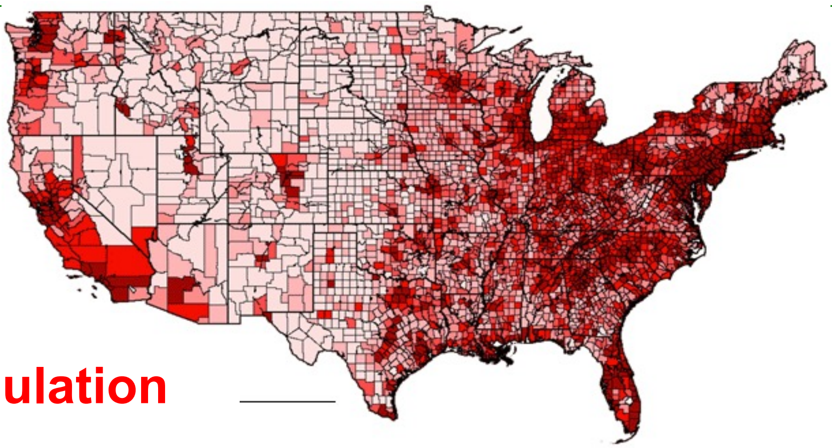
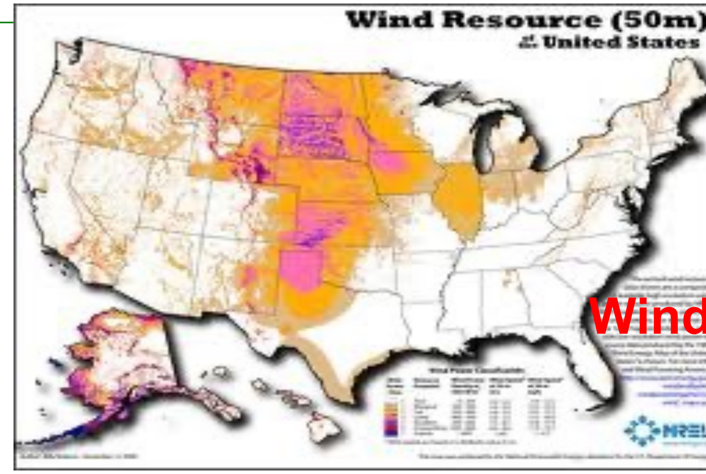
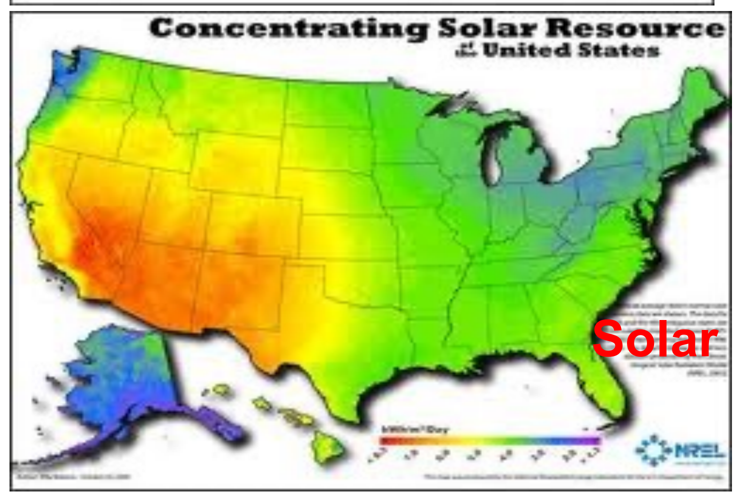
U.S. Wind and Solar Resources



Population





http://www.eia.doe.gov/cneaf/solar.renewables/ilands/fig12.html

Best wind and solar sources are far from load centers.

Distance provides diversity of sources.

Transmission networks must play a central role in integration.

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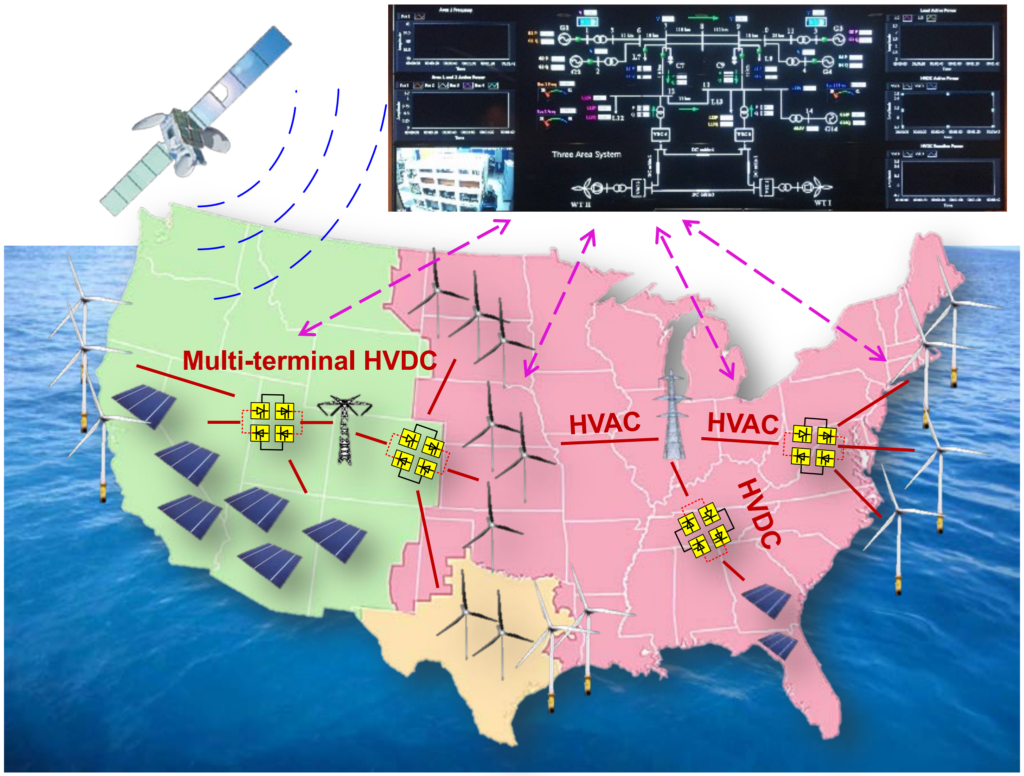
CURENT Concept



- High penetration of renewable energy sources
- Flexible DC and AC transmission
- Accommodate load and source variability, responsive load
- Improved situational awareness, ultra-wide-area control

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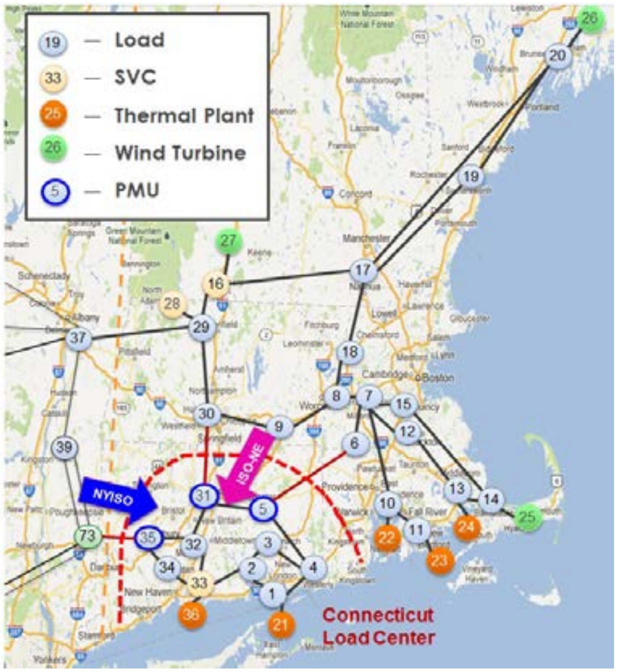
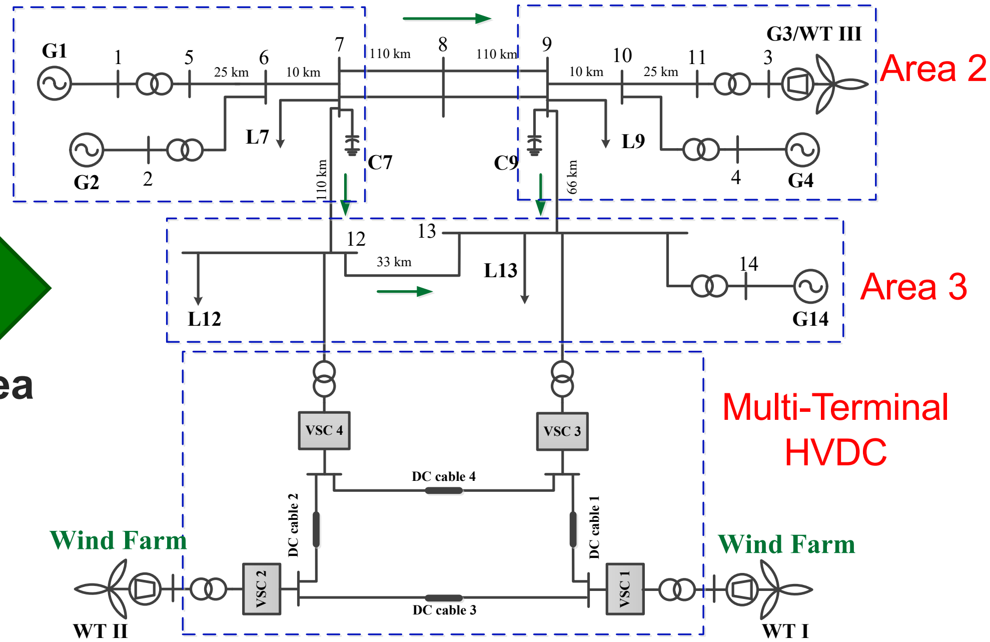
Hardware Grid Emulation System Testbed (HTB)



Three-Area System



- Emulate various grid scenarios with interconnected clusters of scaled-down generators, loads, and energy storage.
- Demonstrate tools developed by research thrusts.

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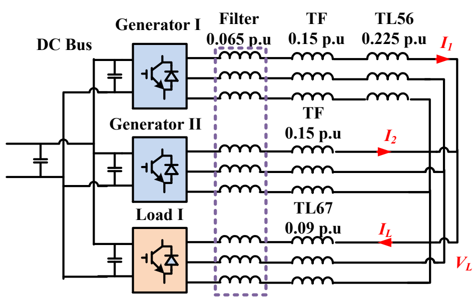
CURENT Hardware Testbed (HTB) - Emulation Structure

Emulator System Structure

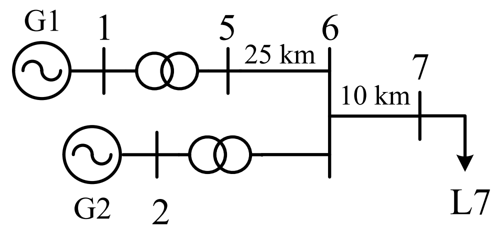


$V_{base} = 61.2\ \text{V}$ $\quad I_{base} = 17.36\ \text{A}$

$P_{base} = 1302\ \text{VA}$ $\quad Z_{base} = 2.88\ \Omega$

Same p.u.

Emulated Power System Structure



$V_{base} = 230\ \text{kV}$ $\quad I_{base} = 255\ \text{A}$

$P_{base} = 100\ \text{MVA}$ $\quad Z_{base} = 528\ \Omega$

- Hardware Testbed (HTB) uses modular, reconfigurable power electronic converters to emulate power system components, and circulate power between them
- Emulate various grid scenarios with interconnected clusters of scaled generators and loads

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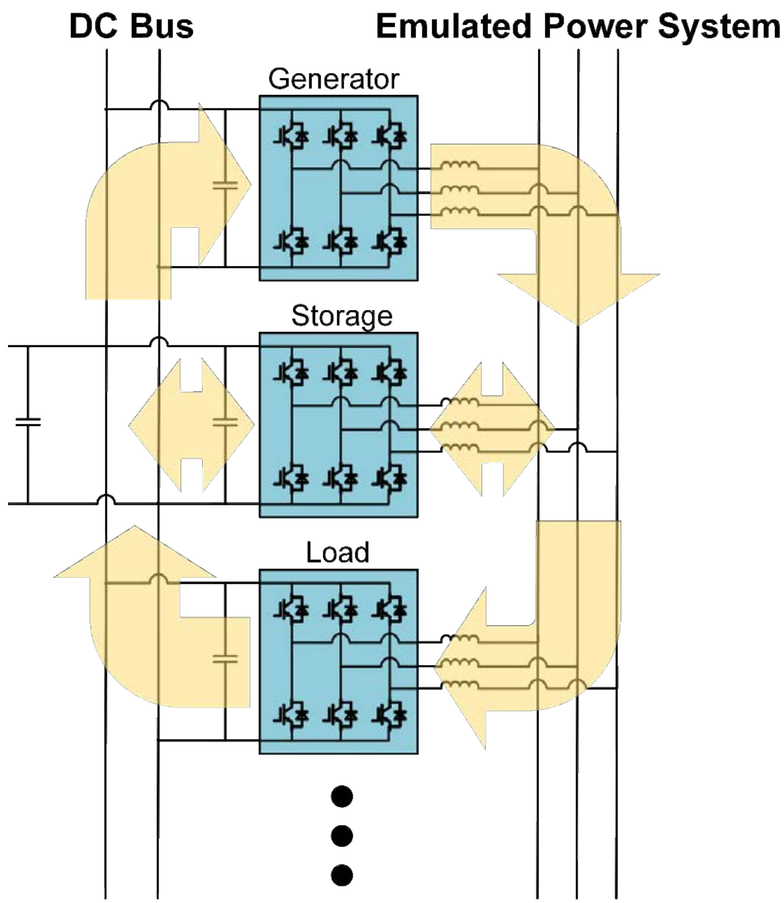
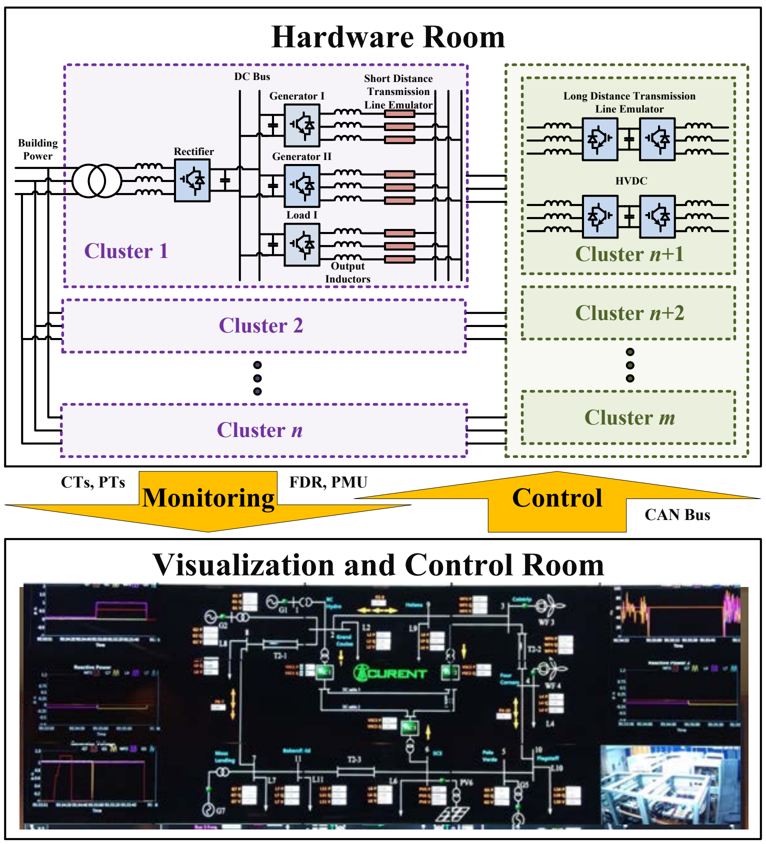
Hardware Testbed (HTB) Background

- Power circulates within a single area
  - Inverters exchange power between DC bus and the emulated power system
  - DC bus makes up losses in the emulated system and inverters



Hardware Testbed Architecture



Hardware cabinets and software are designed to make entire system modular. Multiple simultaneous control functions and software hierarchy established.

Several generation/load cabinets and transmission line cabinets so larger system can be emulated.

Energy storage and responsive load control key to grids with high penetration of renewables.

Virtual synchronous generator control of wind turbine converters and PV converters.

Transmission line fault emulation, FACTS, and power system protection function emulation.

Realized different **scenarios** with high penetration renewables and HVDC overlay.

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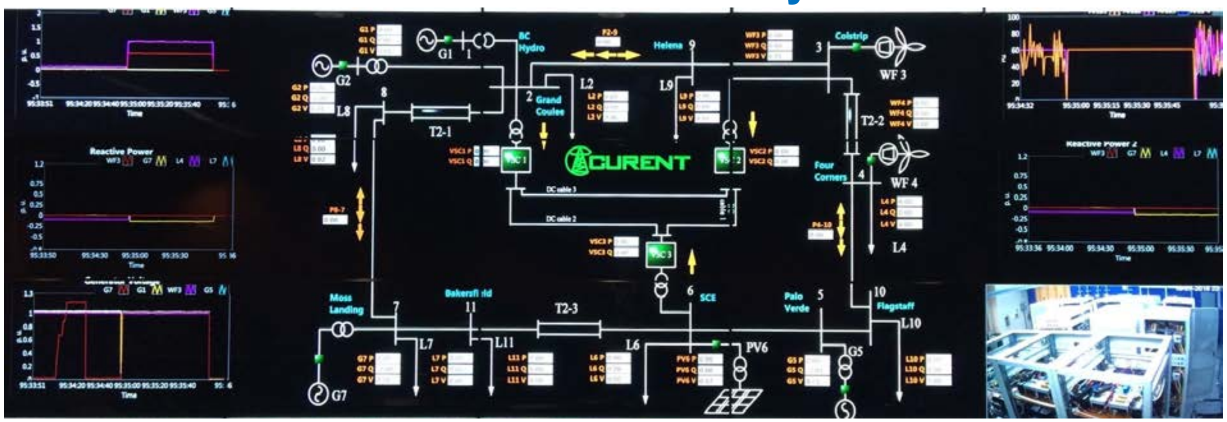
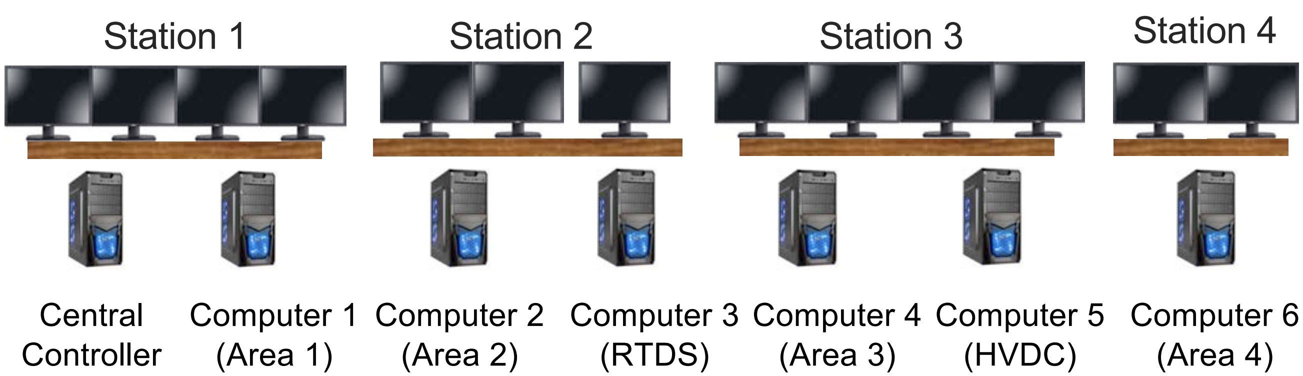
Communication, Control, and Visualization（4 areas）

Visualization Room Layout





Control Center functions

Area control center:

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

Central controller:

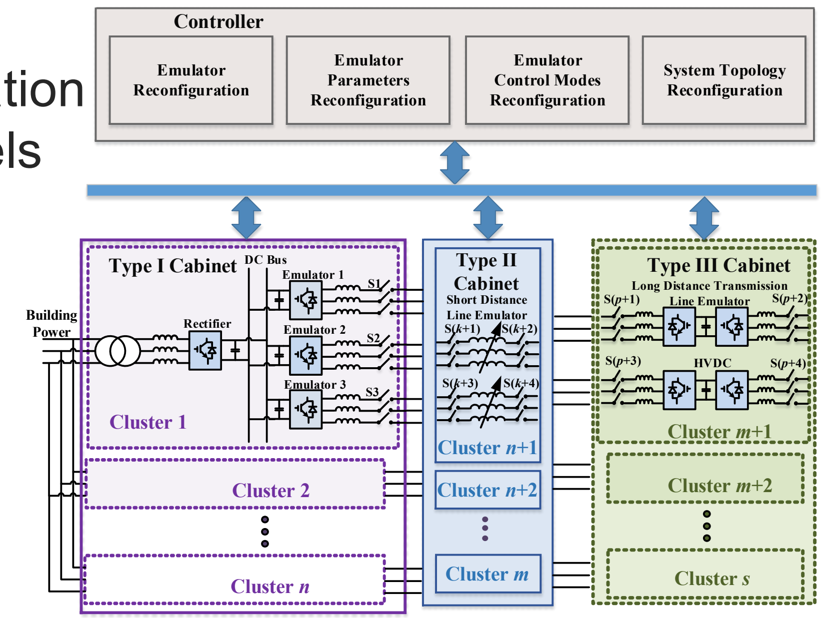
- Only for automatic scenario sequencing and demonstration
- Future system level testing

Visualization computer:

- Only for display of system information on the video wall

Reconfigurable Software and Hardware

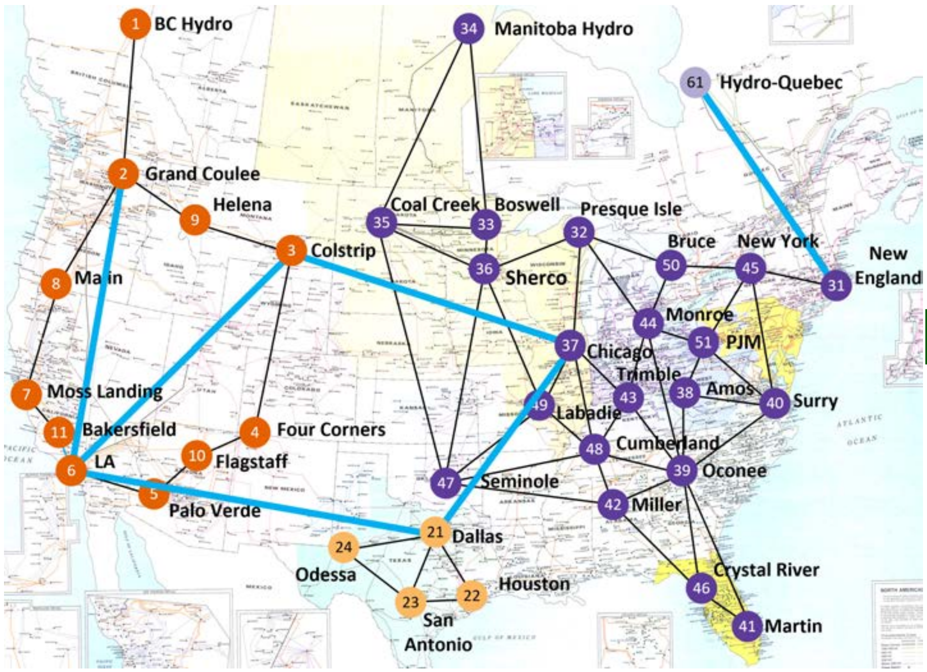
- All Type I (area) and Type III (long ac lines or dc lines) cabinets are connected to Type II (variable inductor) cabinets
- Local line impedance can be controlled to the desired value
- Different system topologies reconfiguration are through front panels of variable inductor cabinets
- Each area and central controller has identical structure which can control any area cabinet



Reconfigurable HTB system


Type II cabinets

North American Grid with HVDC Overlay



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

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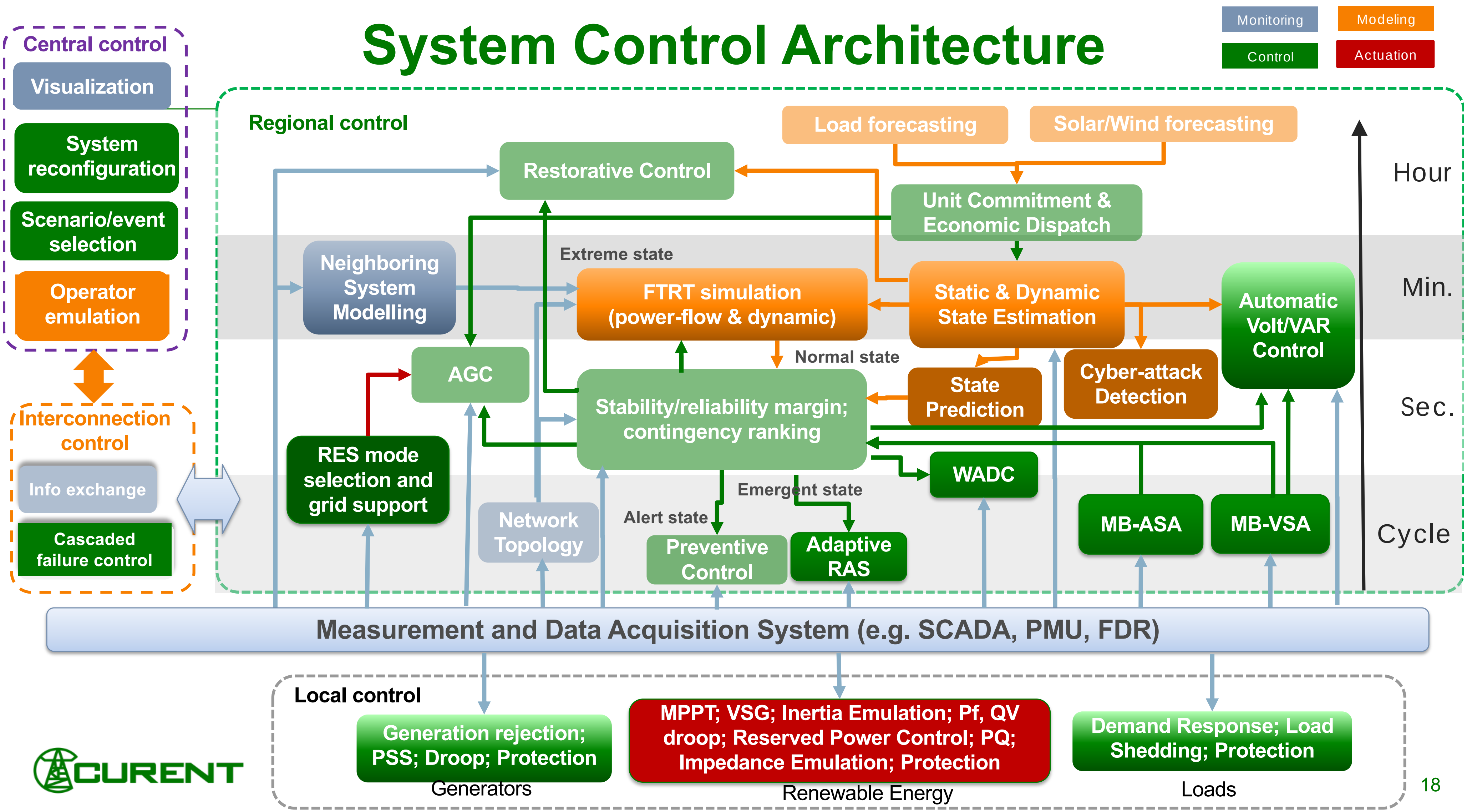
System Control Architecture



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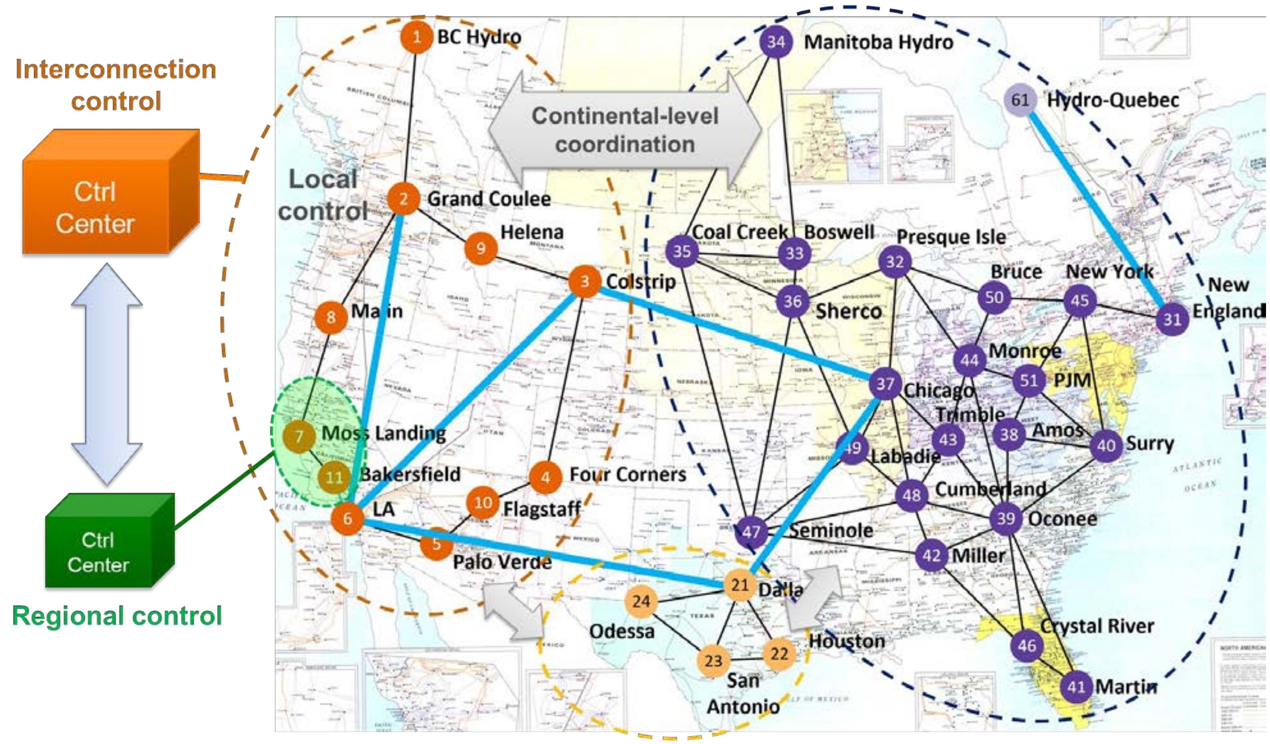
National Grid HTB Demonstration Scenarios

- Demonstrate security/stability assessment based HTB control system
- Demonstrate ability of HVDC overlay to provide continent-level coordination between the three grids: EI, ERCOT, WECC
- Evaluate high penetration (>80%) of renewables in grid



Emulator Development Summary

Emulators

Generator Emulator	Synchronous generator
Load Emulator	Single and three-phase induction machines, variable speed drives, EV chargers, data center power supplies, LED lighting
	Constant impedance, constant current, and constant power load (ZIP)
Wind Emulator	Type IV full converter wind turbine with permanent magnetic synchronous generator (PMSG)
	Type III wind turbine with doubly-fed induction generator (DFIG)
Solar Emulator	Solar panel with two-stage PV inverter
Transmission Line Emulator	Back-to-back converter to emulate AC transmission lines with FACTS compensation device and fault emulation
Energy Storage Emulator	Batteries (Li-Ion, Pb-Acid, and flow), flywheels
RT Simulator Interface	Integrate RTDS with HTB
HVDC Emulator	Multi-terminal HVDC represents lines and converter stations
Combined Model Emulator	Emulate combined models in single emulator
Fault and Protection Emulator	Emulate short circuit faults – demonstrate system relay protection

Voltage Type

Current Type

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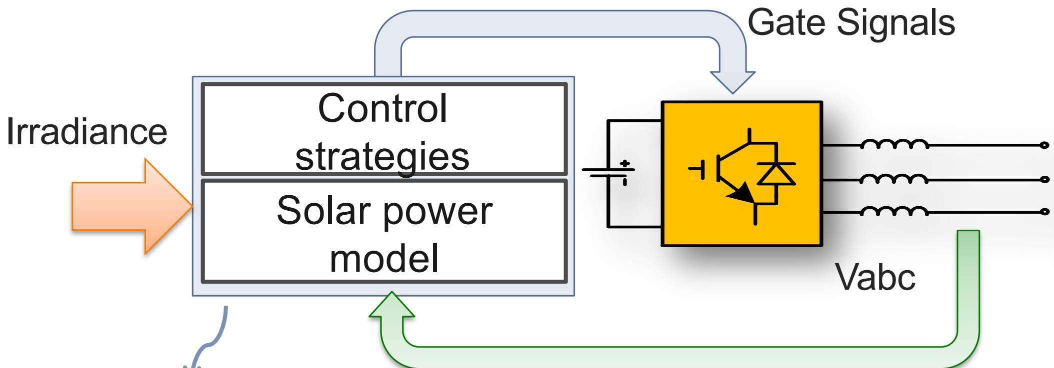
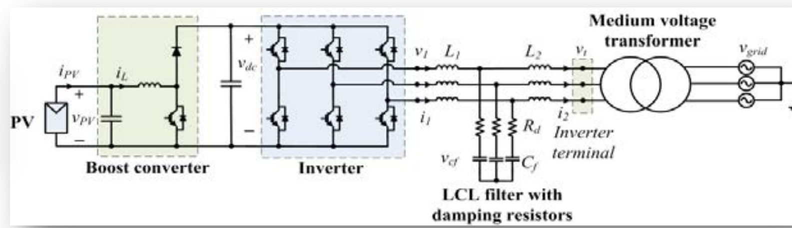
Solar Power Emulator



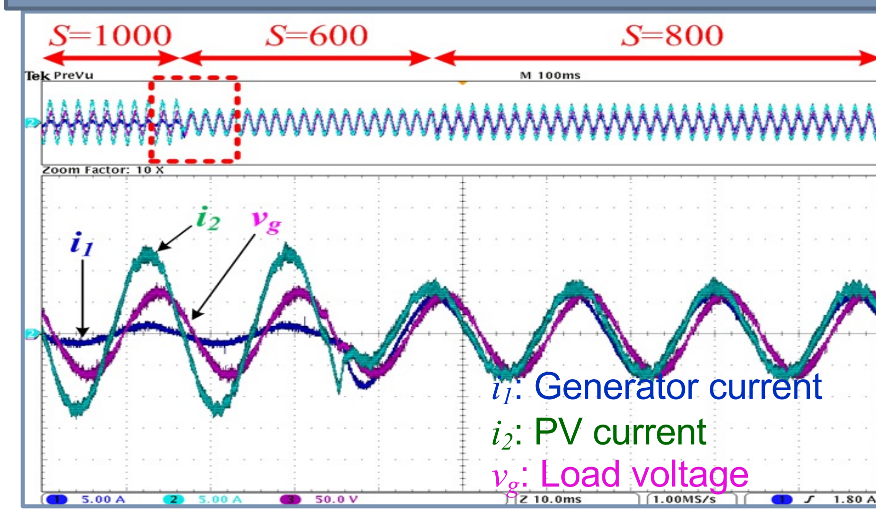
Physical Models
- PV panel model considering the irradiance and temperature
- Boost converter model
- Inverter model including the LCL filter

Control strategies
- MPPT and reserved power control
- Droop and inertia emulation
- Reactive power control
- Low voltage ride through (LVRT)

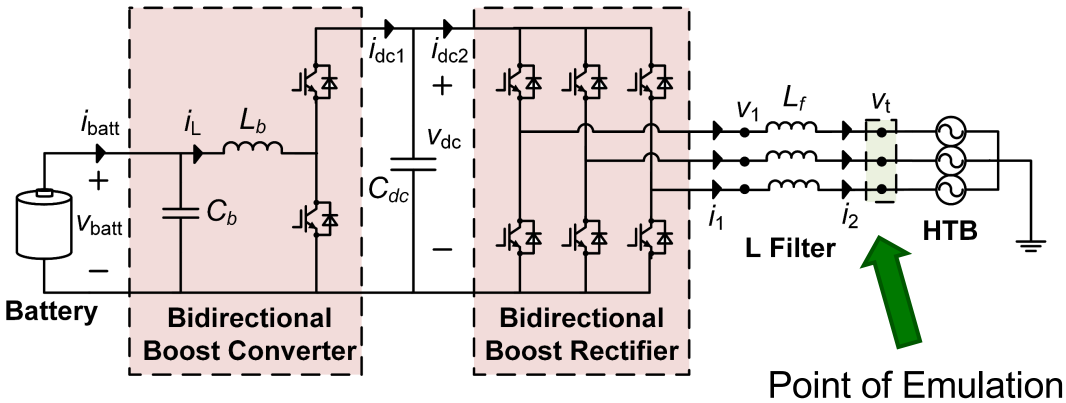
Two-stage PV inverter

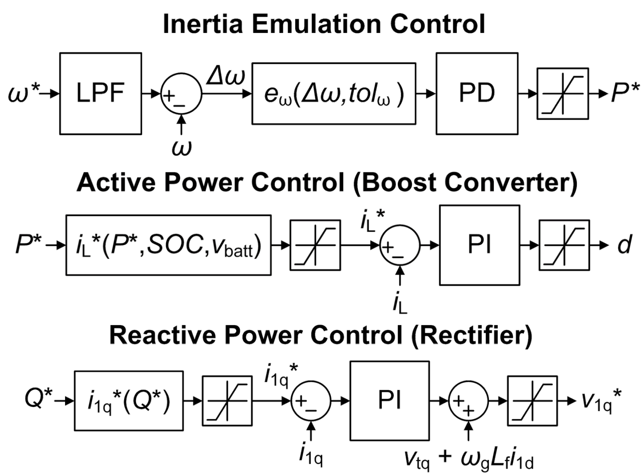


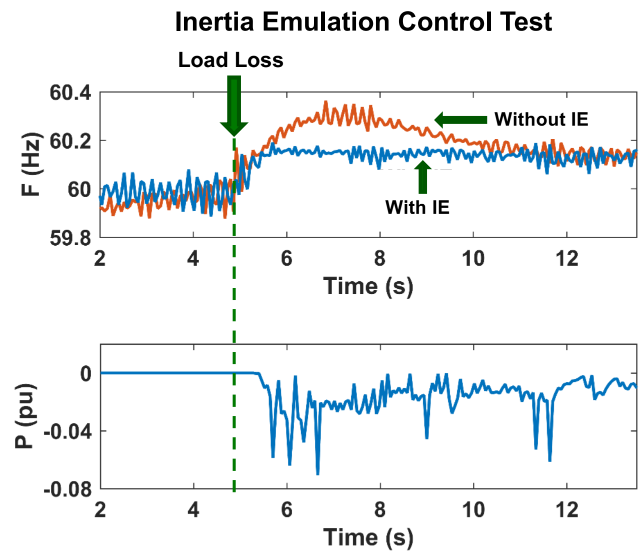
MPPT under irradiance (S: W/m^2) change



Battery Energy Storage Emulator



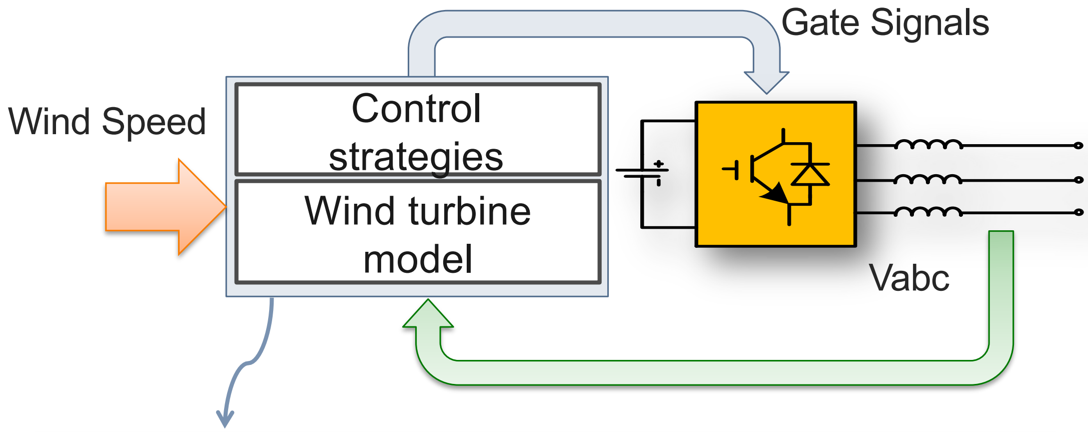




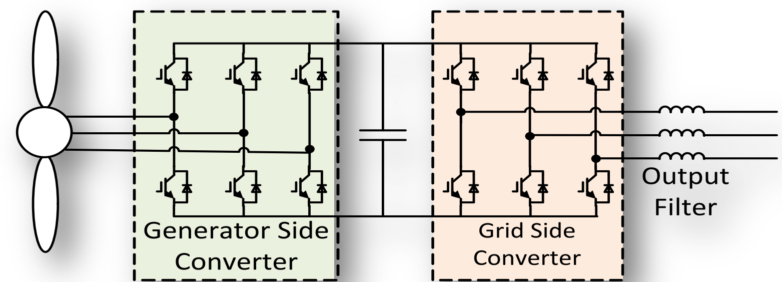
<u>Emulator Attributes</u>

- Two modes of operation: Command and Inertia Emulation
- Choice between Lithium Ion, Lead Acid, Flow batteries
- Constant current – constant voltage charging algorithm
- Independent active and reactive power control
- Operates on its own HTB inverter

Wind Turbine Emulator



Full converter with permanent magnetic synchronous generator



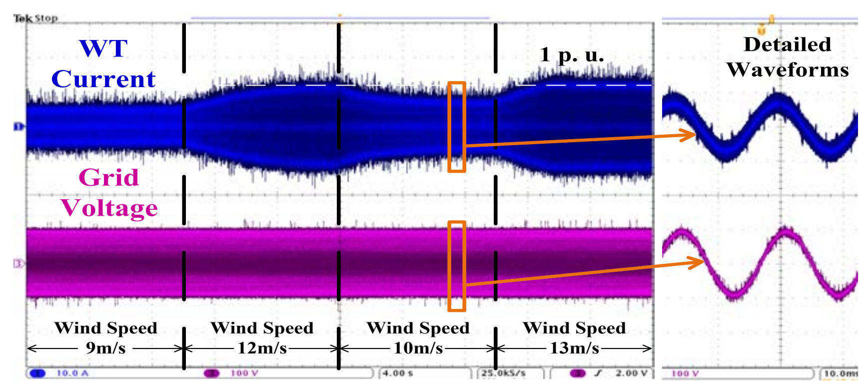
Physical Models

- Wind power model and pitch model
- Electrical and mechanical models of PMSG
- Average model of the two converters

Control strategies

- MPPT and reserved power control
- Droop and inertia emulation
- Reactive power control

Variable wind speed experiment



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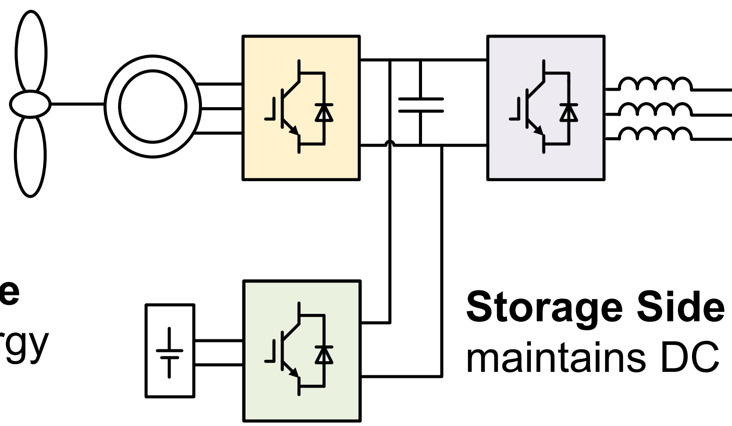
Virtual Synchronous Generator (VSG) Control of Type-4 Wind Turbine

Objective: Let renewable energy sources behave like the synchronous generators in power system

Machine Side Converter
controls wind turbine speed
- MPPT
- Follow grid demands

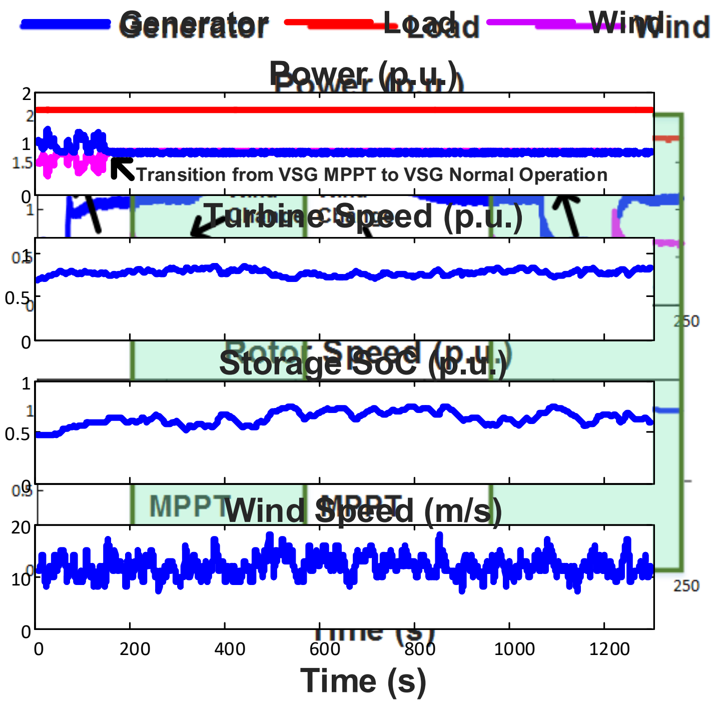
Grid Side Converter
emulates the generator behavior
- Dispatch-able
- Variable emulated inertia



Minute Level Energy Storage
- Provide energy buffer

Storage Side Converter
maintains DC Voltage

Comparison between VSG MPPT and traditional MPPT



VSG can track maximum power point, and provide inertial response

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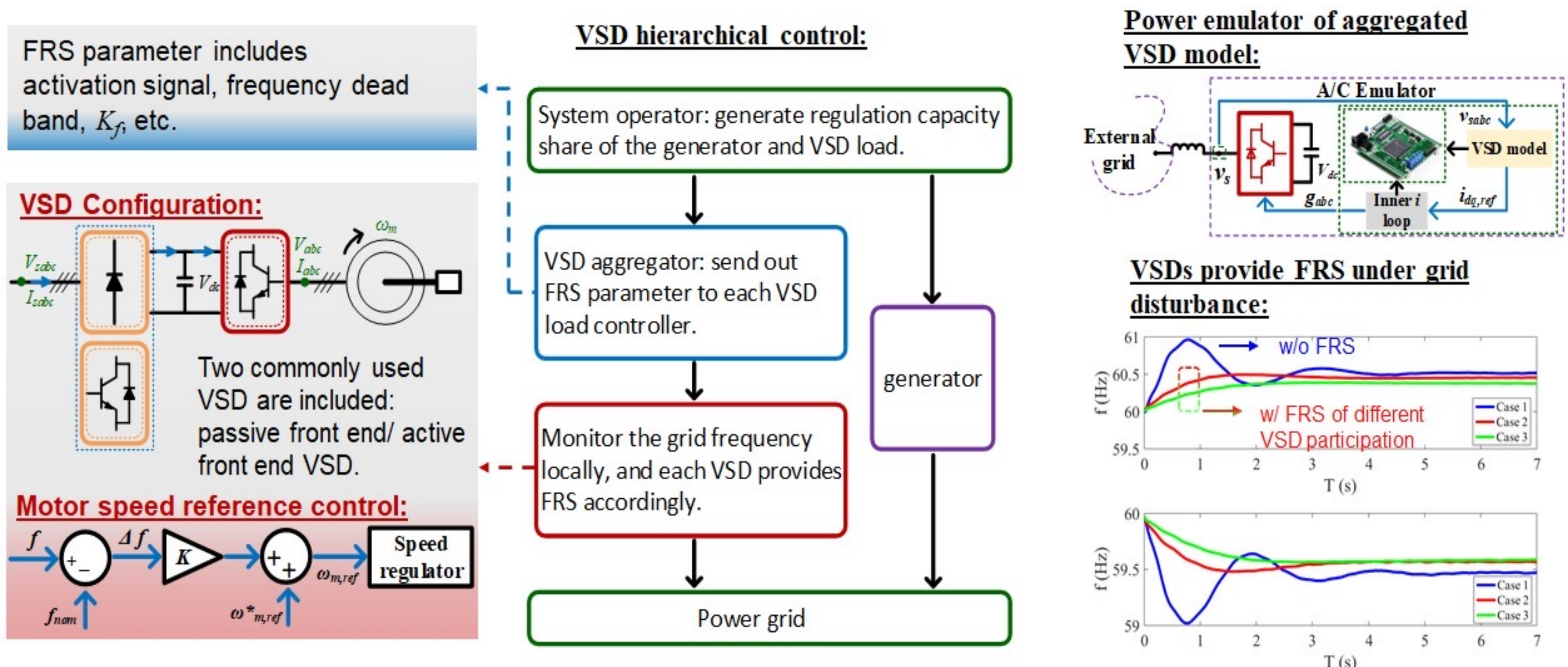
VSD Loads Hierarchical Control for Grid Frequency Support



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

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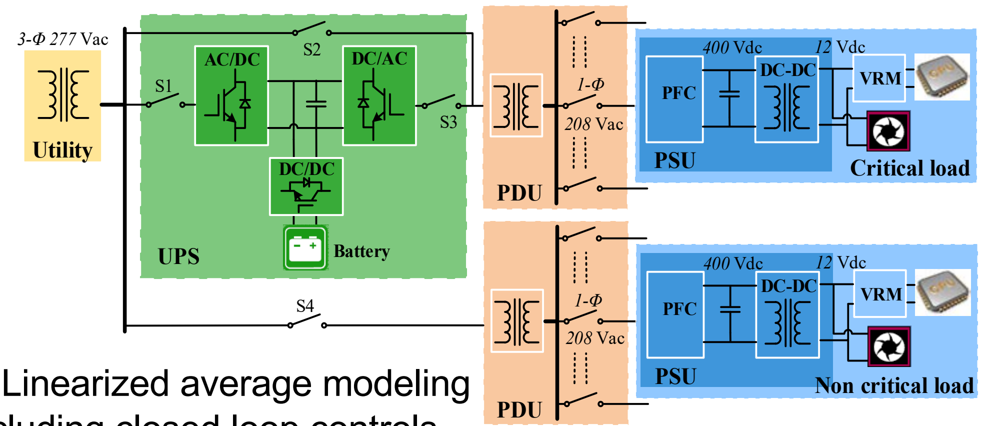
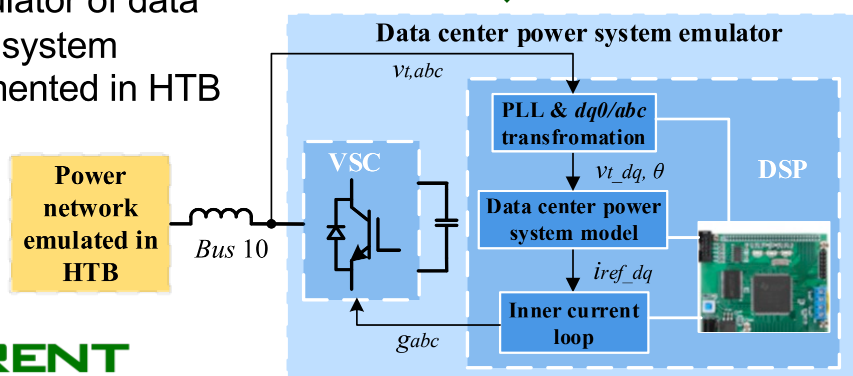
Converter-Based Emulator of Data Center Power Supply System

1. Typical structure of a data center ac power distribution system

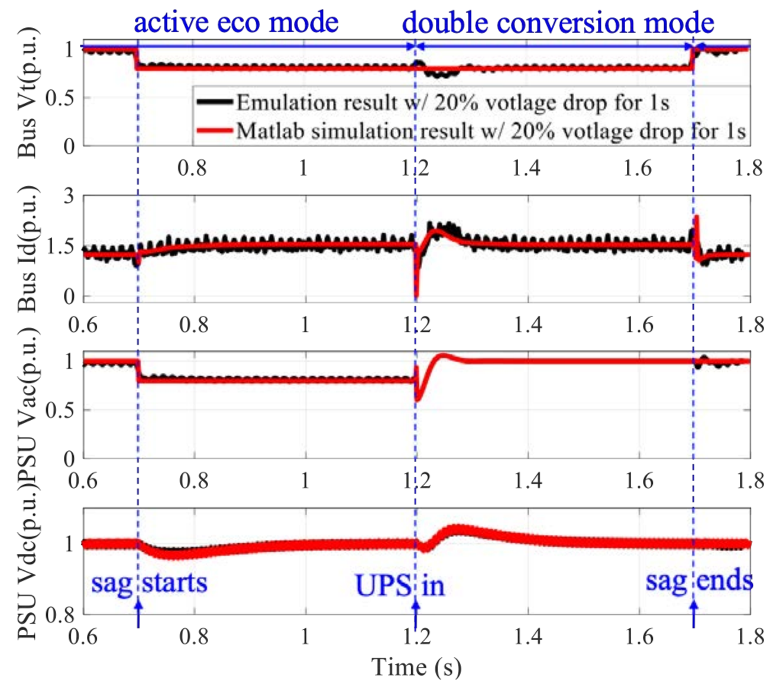


2. Linearized average modeling including closed loop controls

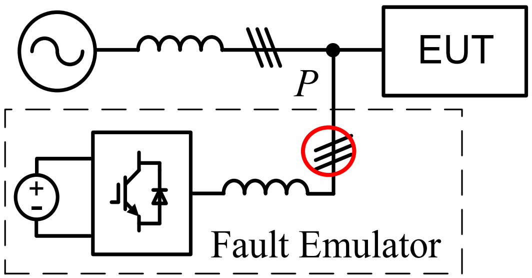
3. Emulator of data center system implemented in HTB



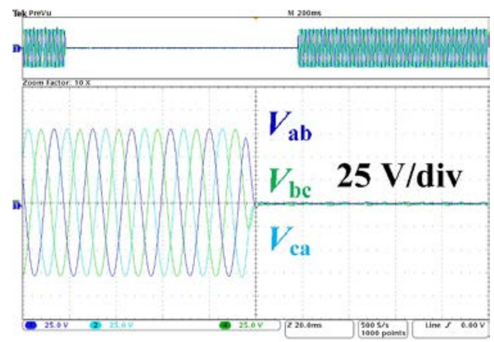
4. Dynamic performance with 20% voltage sag transient condition.



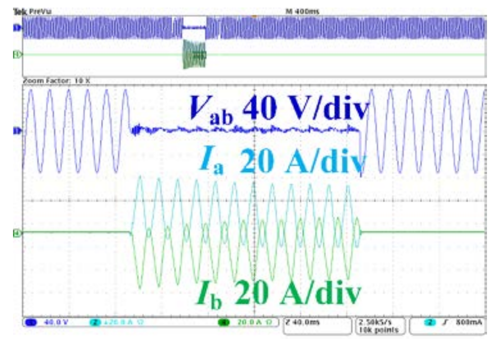
Bus Short-Circuit Fault Emulation



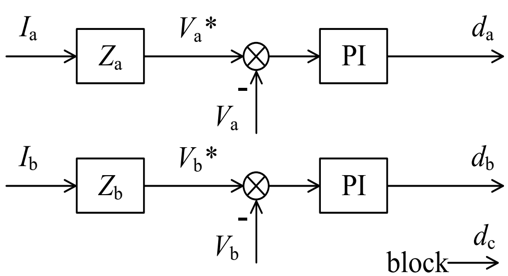
Realize short-circuit faults by controlling the corresponding phase of emulator terminal voltages to zero



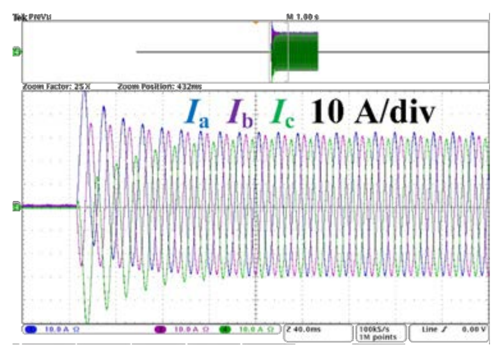
Voltages of three-phase short circuit



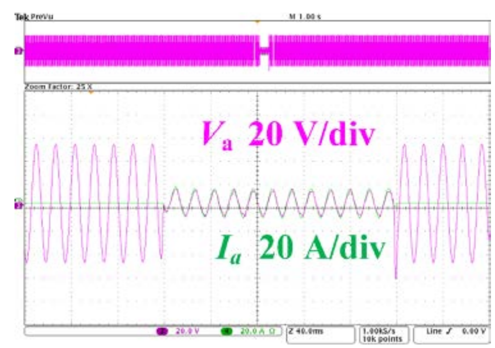
Line-to-line short circuit



Control block diagram of double-line-to-ground fault

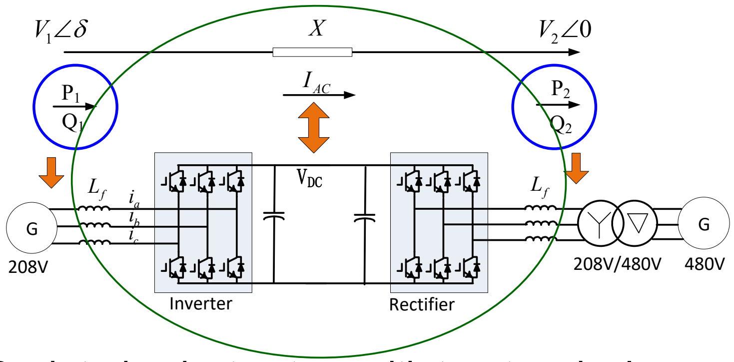


Currents of three-phase short circuit

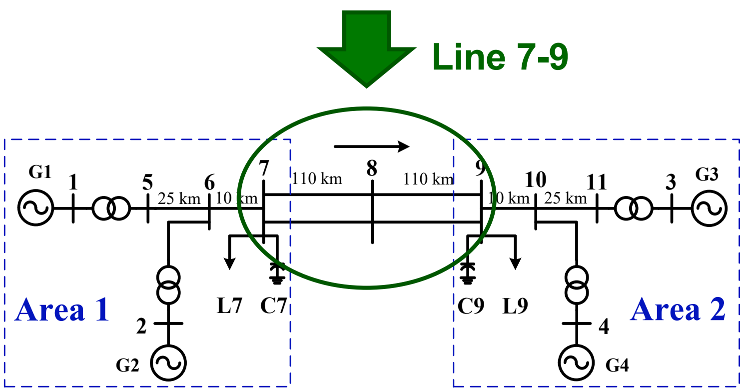


Single-line-to-ground short circuit with 1 Ω grounding resistance

AC or DC Transmission Line Emulator



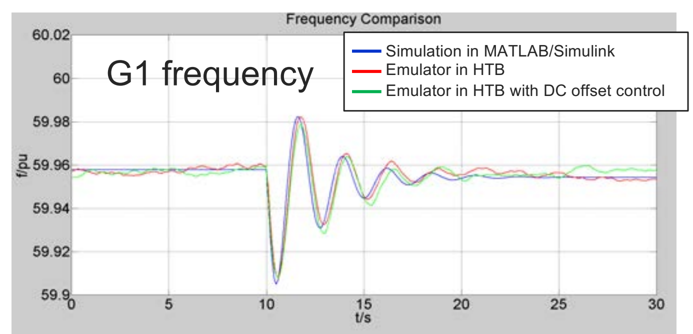
Back-to-back structure with two terminals



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)



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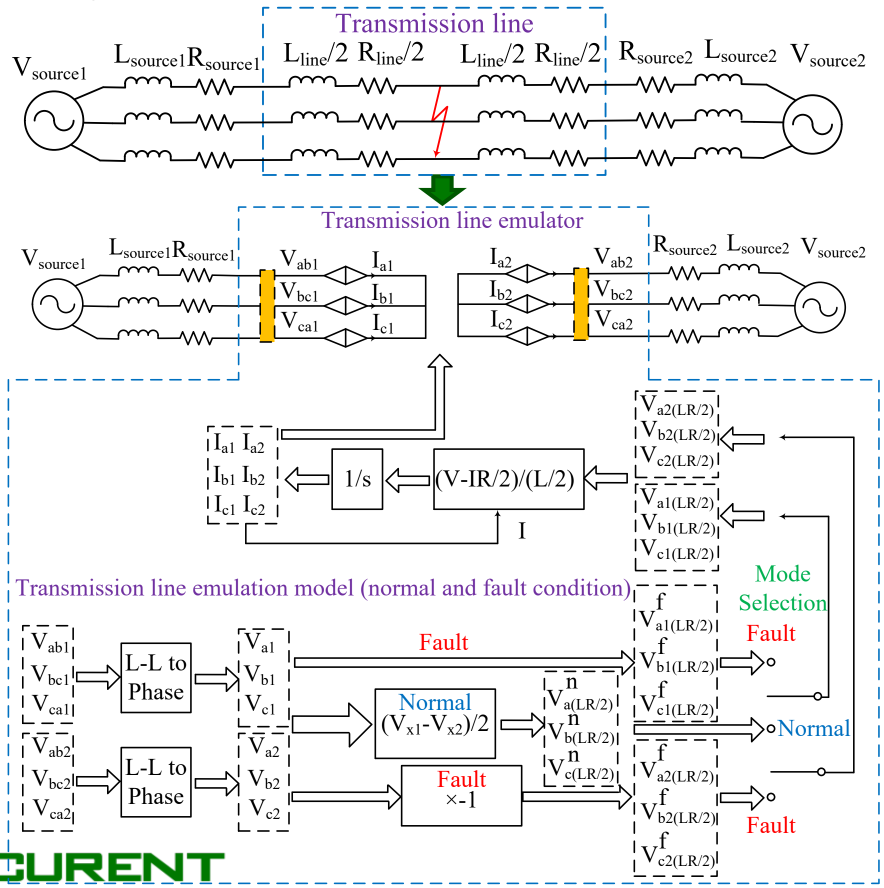
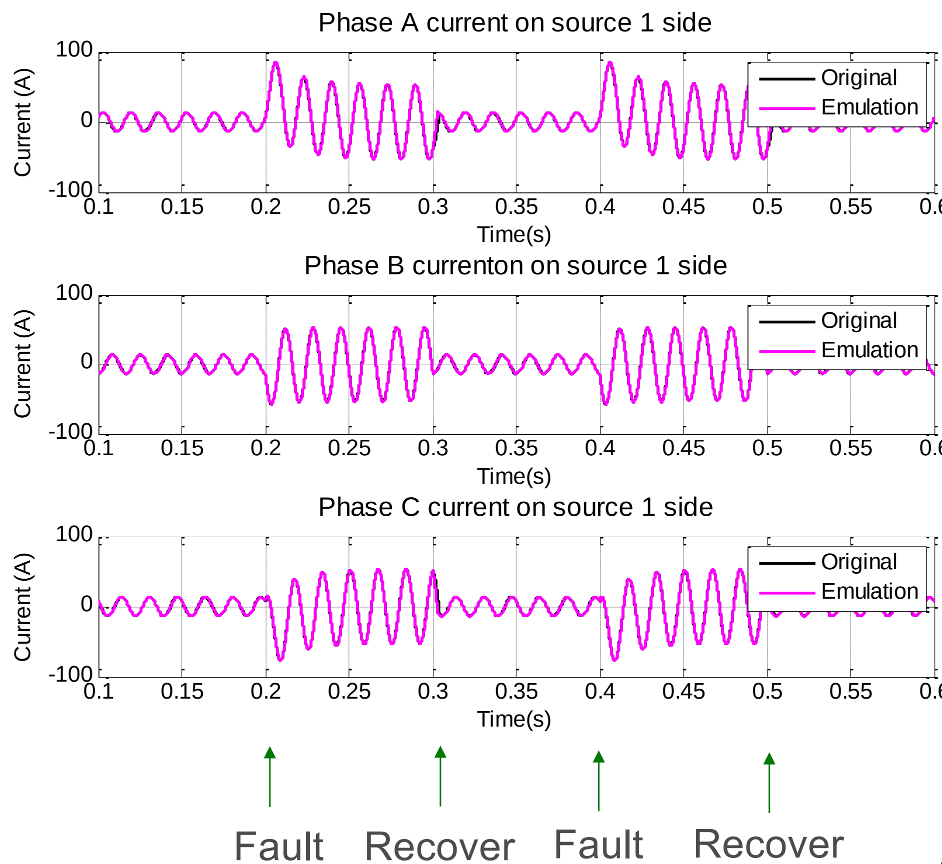
Transmission Line Fault Emulation

❑ System model

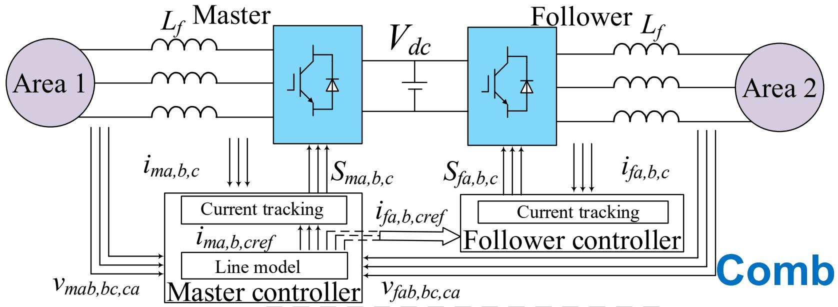


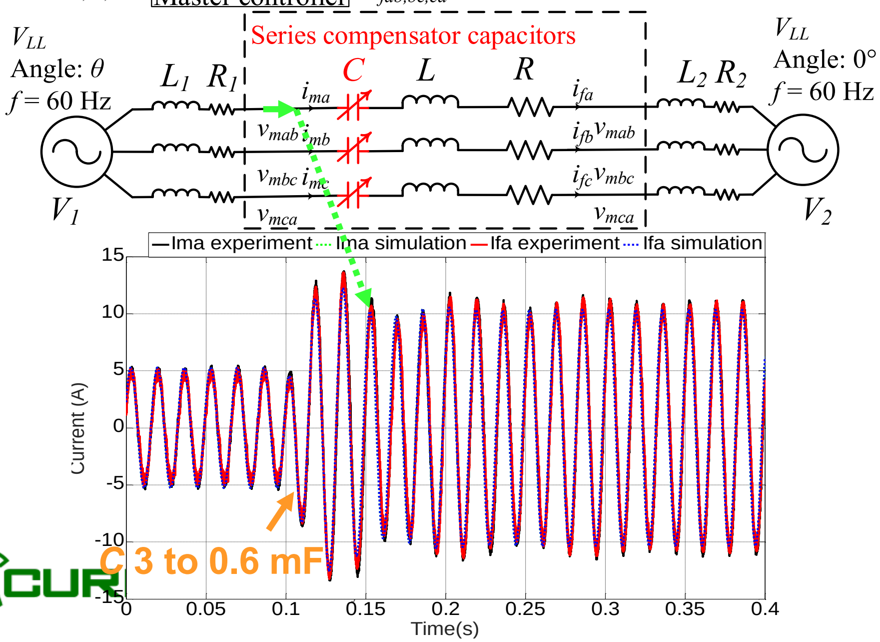
❑ Simulation Verification



Transmission Line with Combined FACTS Emulation

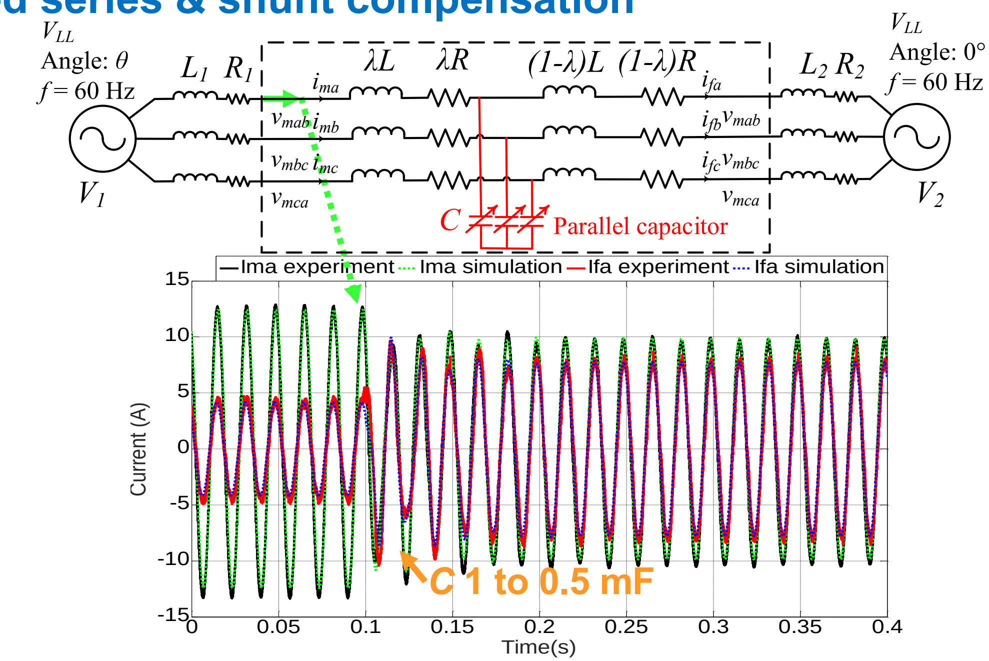
Transmission line emulator





- Emulated transmission line models
  - Combined series compensation
  - Combined shunt compensation
  - Line-to-line fault
  - Traveling wave model

Combined series & shunt compensation

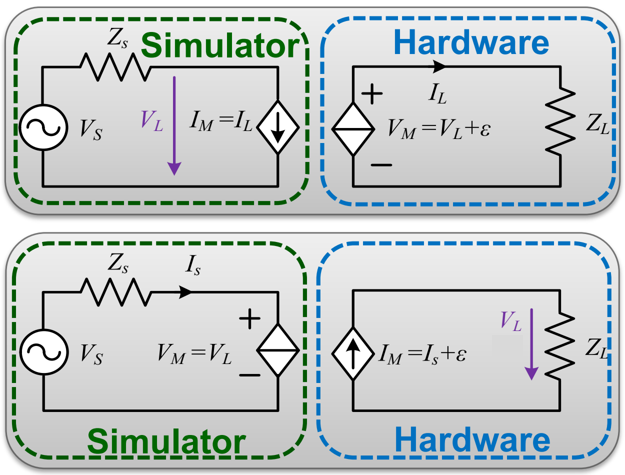


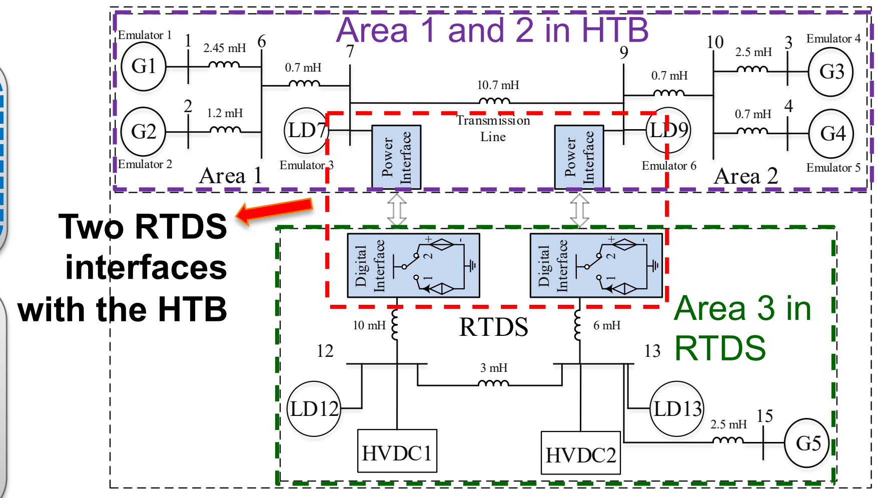
RTDS Interface with HTB

Interface Algorithms:

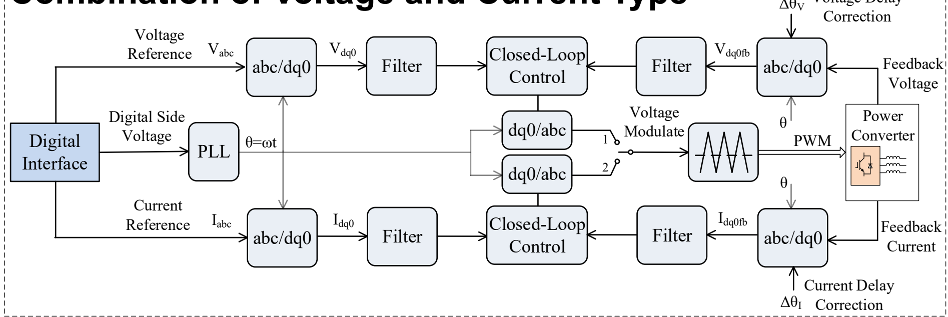
Voltage Type

Current Type





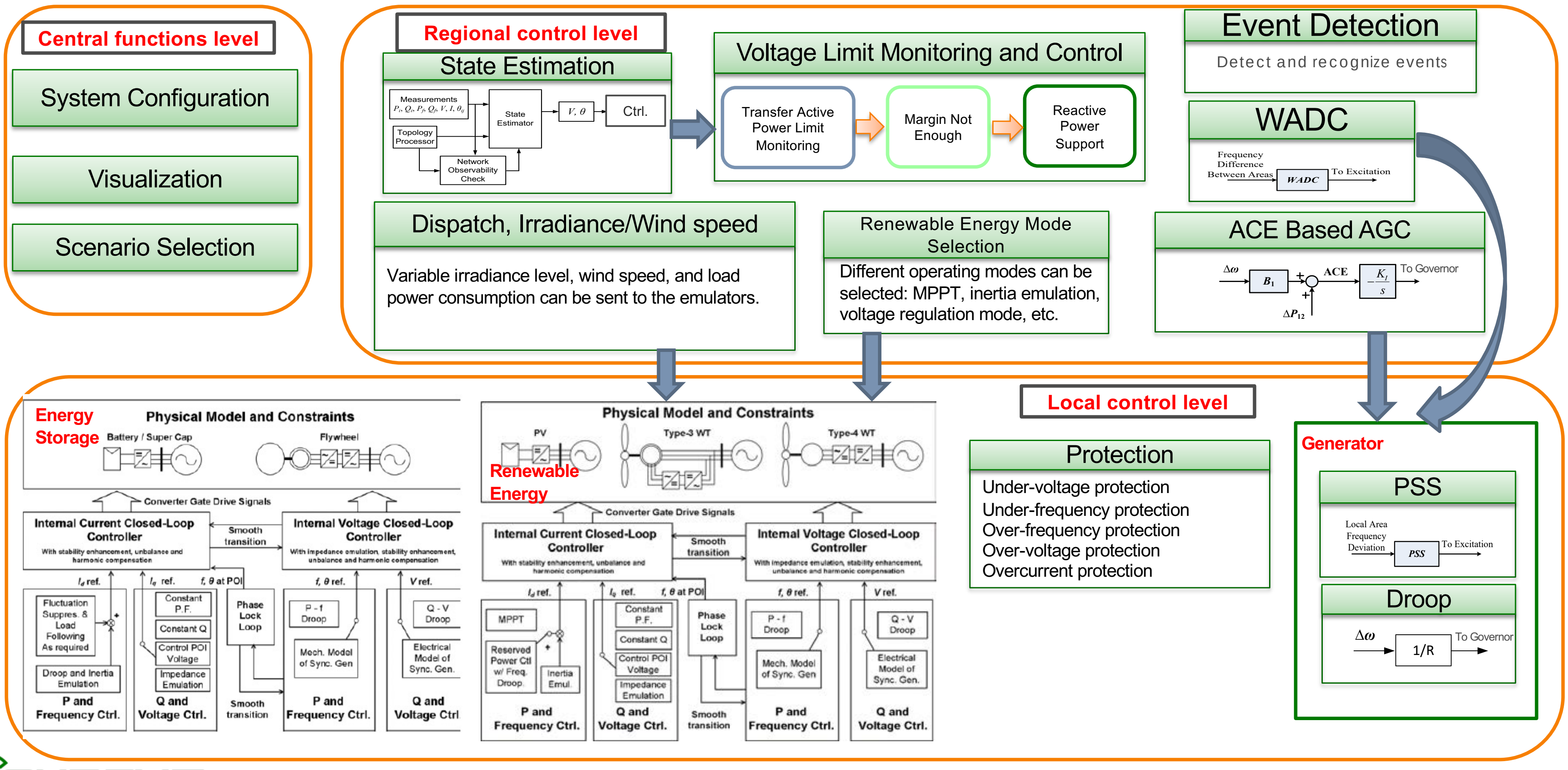
Combination of Voltage and Current Type



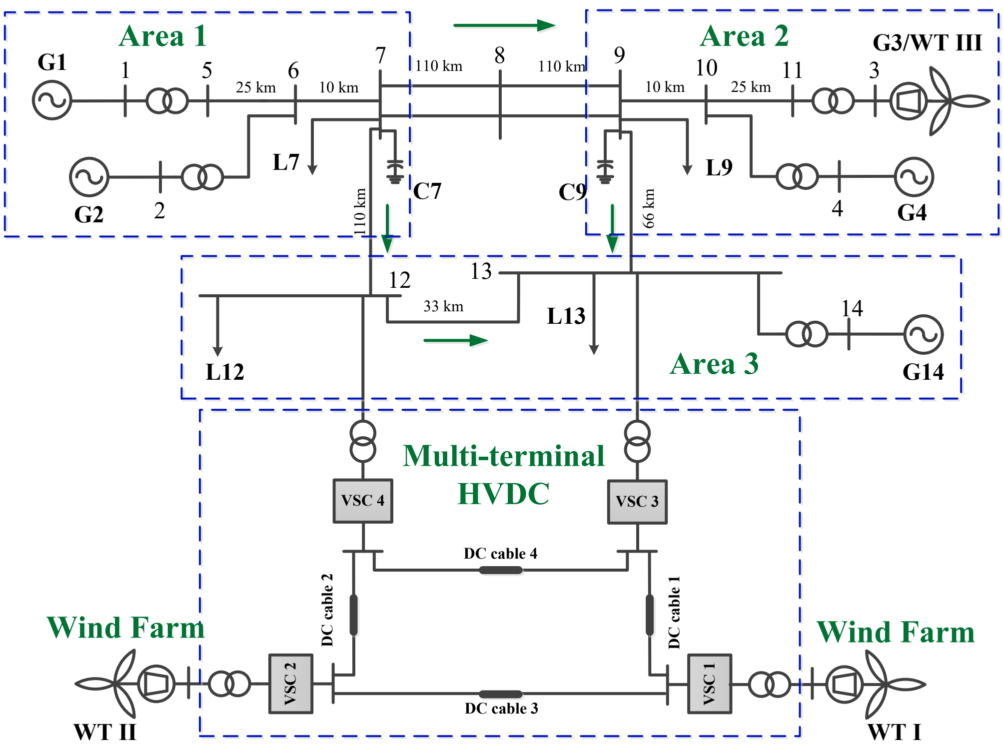
RTDS Interface Attributes

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

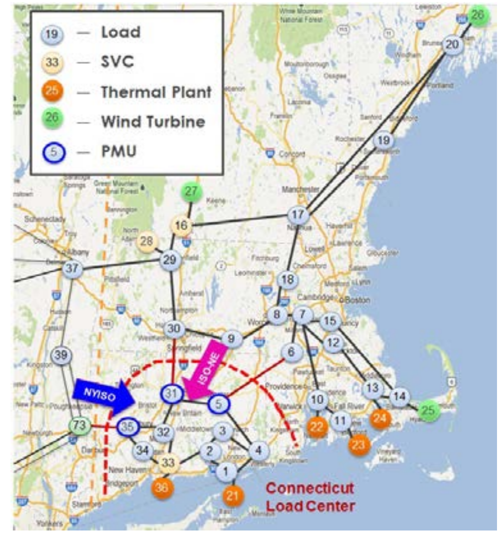
Interoperability: Multiple Simultaneous Control Functions



3-Area CURENT HTB Structure



Three-area system including multi-terminal HVDC and wind farm



Three-area system:

- Three areas interconnected by three long transmission lines (220 km, 220 km, and 132 km respectively)
- Area 3 connected to a multi-terminal HVDC (MTDC) system with DC lines (two 100 km, one 60 km, and one 70 km)

Scenario - High Renewable Penetration – Inertia Emulation

Scenario

- Replace G2 by an onshore wind farm.

  Together with offshore wind provided by HVDC, system renewable penetration can reach 80%. Event triggered by a HVDC converter failure.

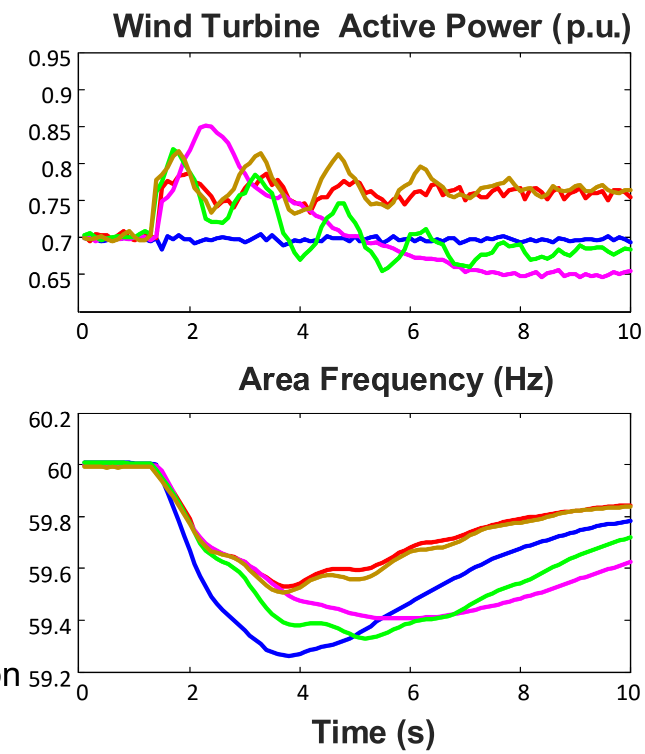
Solution

- Frequency and voltage support from onshore wind farm and the HVDC converters
- Curtailment and voltage mode control when necessary
- Integration of energy storage to further enable grid support controls

Expected outcome

- System frequency and voltage within acceptable range

HTB scenario test results



- Base case with generator
- MPPT
- MPPT with inertia emulation
- Voltage mode
- Voltage mode with storage

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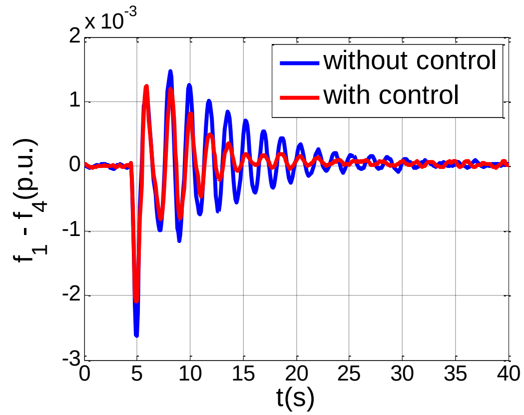
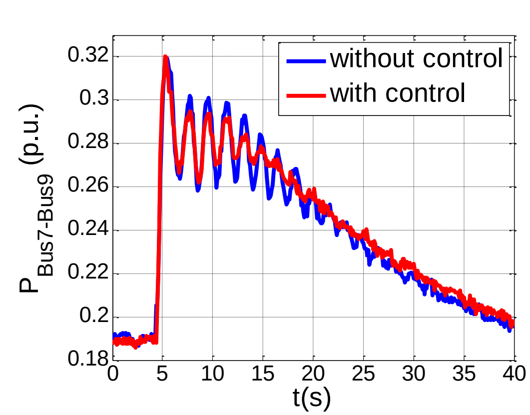
Scenario – Wide-area Damping Controller

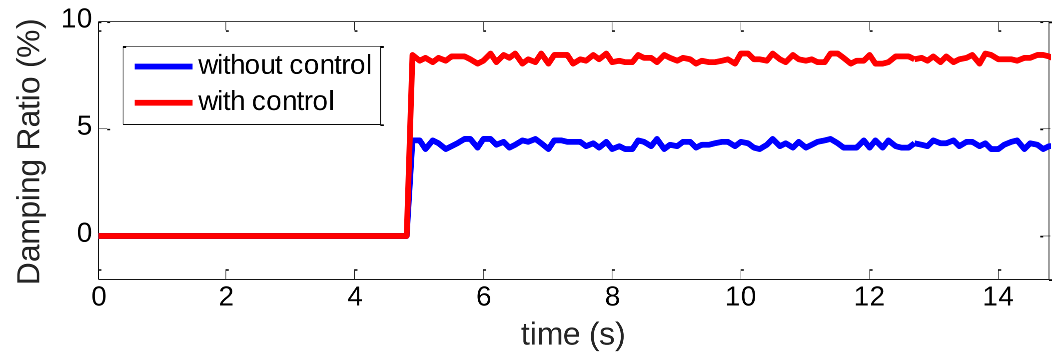
- **Scenario**
  - 50% renewable penetration
  - One poorly damped inter-area oscillation mode between Area 1 and Area 2
- **Wide-area Damping Controller (WADC)**
  - Based on the measurement-driven model, which is identified by using ring-down data and ambient data
  - Controller input: frequency difference between Area 1 and Area 2
  - Controller output: added to exciter voltage reference of Generator 1
- **System disturbance**
  - Load increase (Bus 9, 0.7 p.u. to 1.1 p.u.)



Frequency deviation



Tie-line power, Bus 7-Bus 9



Estimated damping ratio using Matrix Pencil

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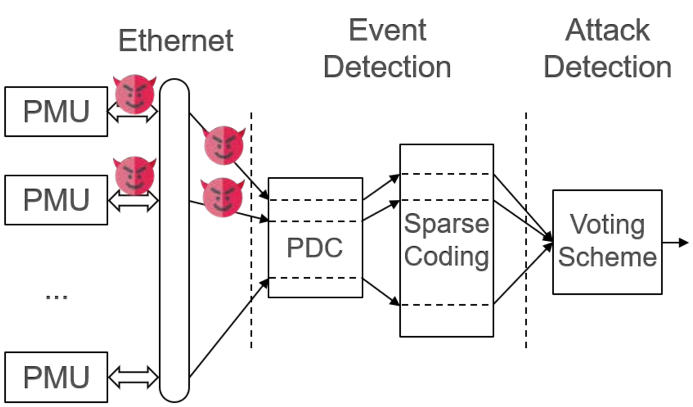
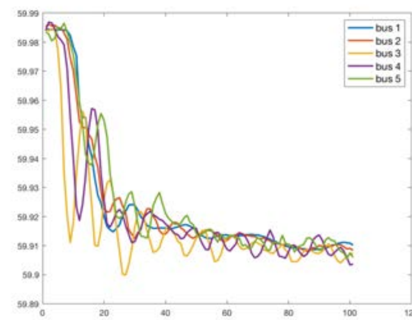
Synchronized Cyber Attack and Detection on HTB

- **Vulnerabilities and Threat Model**
  - Protocol IEEE C37.118 has poor security mechanisms and is vulnerable to cyber attacks such as eavesdropping, frame manipulation, interruption, and bad data injection.
  - Attacker is assumed to be able to compromise a large portion of PMUs in the phasor network but not all PMUs; implemented by TCP hijacking on HTB.
  - Assume that the attack and real event will not happen at the same time.

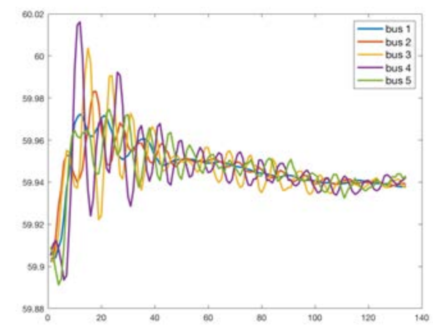


Scheme Overview

- **Multiple Event Analysis**
  - Proposed a multiple-event analysis based on sparse coding to detect and recognize multiple, involved single events, i.e., generator trip, loading shedding and line trip. 100% detection accuracy can be achieved on single event detection.
  - When a real event happens, all buses should respond correspondingly. Also, detection results on different buses



Generation Trip



Load Shedding

- **Attack Detection**
  - Voting scheme is used to perform attack detection. Events that can only be detected in less than 50% of the PMUs are classified as false events that were launched by an attacker.

Scenario – Measurement-Based Voltage Stability Assessment and Control for Load Area (3-Area)

- **Collapse scenario**: load increase on Bus 13 until system collapses.
- **Stable scenario**: with the same load increase, the remedial action (Q support from MTDC) is taken against the voltage instability triggered by the stability margin monitoring.

New MBVSA algorithm:

Rebuild a *N*+1 buses equivalent (For 3-area HTB, *N* = 2) using boundary buses measurements.

↓

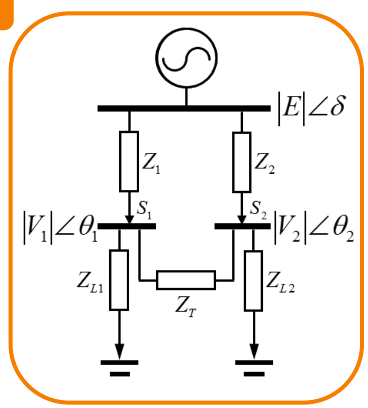
Calculate the transfer limits for each tie line.

↓

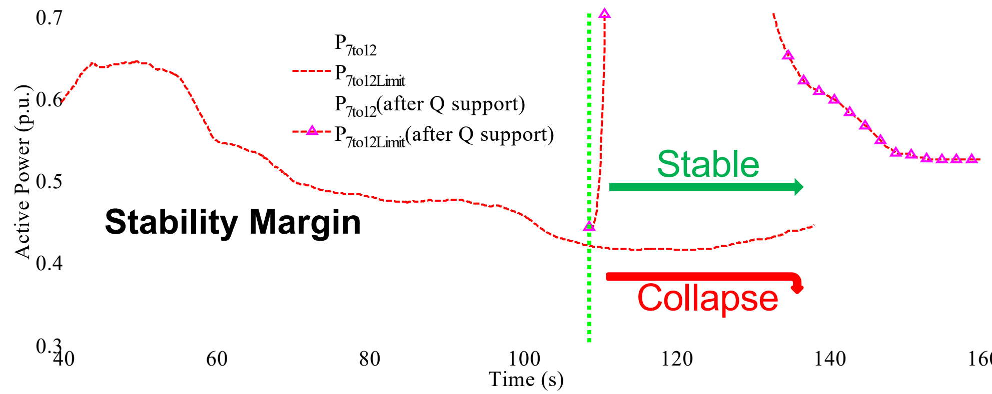
Monitor the stability margins.

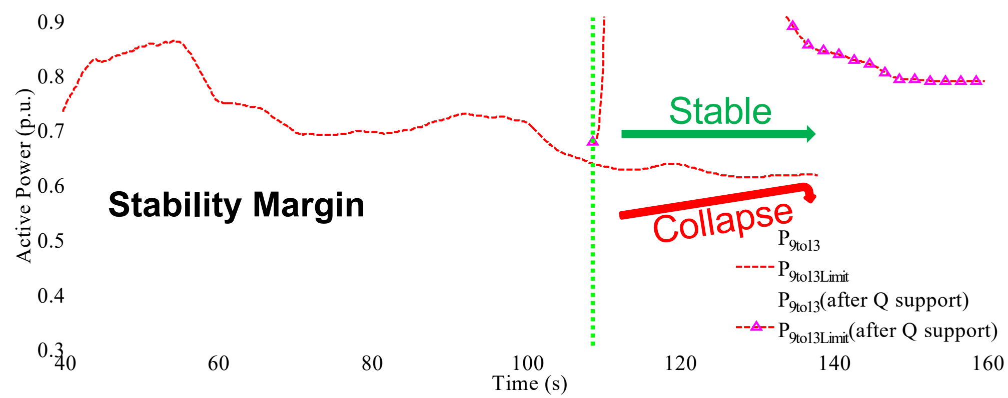
↓

If margin < threshold, take remedial action.



Equivalent circuit model





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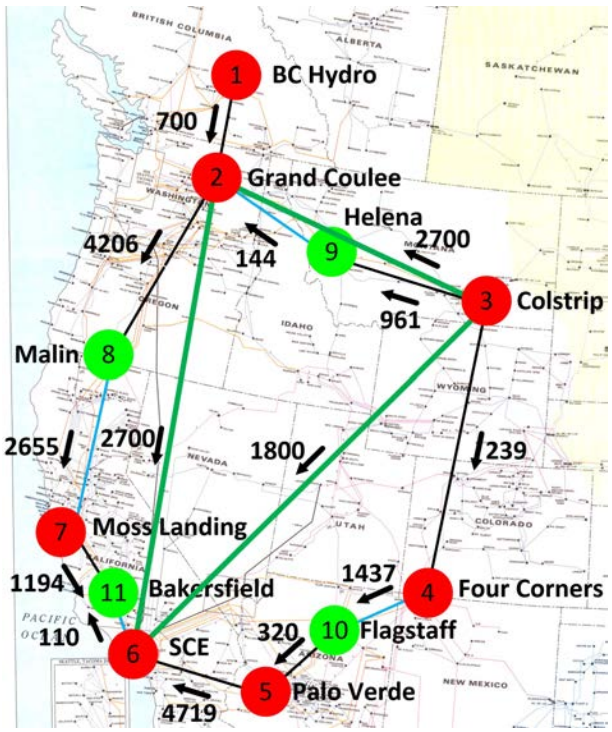
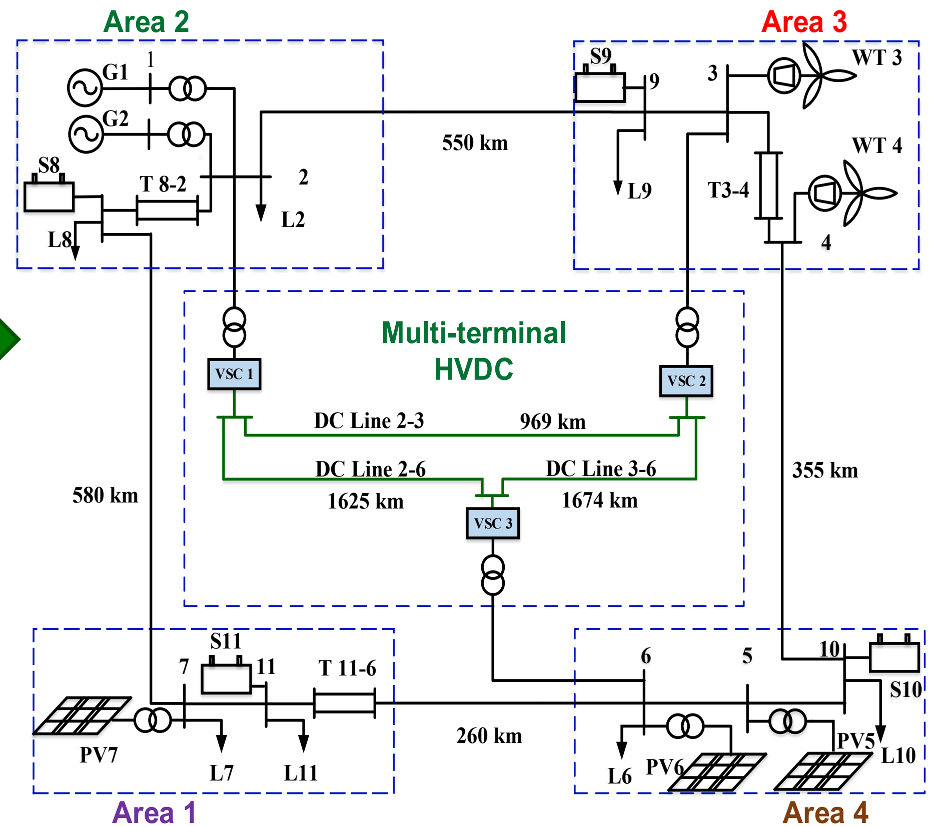
HTB 4-Area WECC Structure



Four-Area System



Four-area system including multi-terminal HVDC overlay, large wind farms, solar energy, and energy storage (battery-based)

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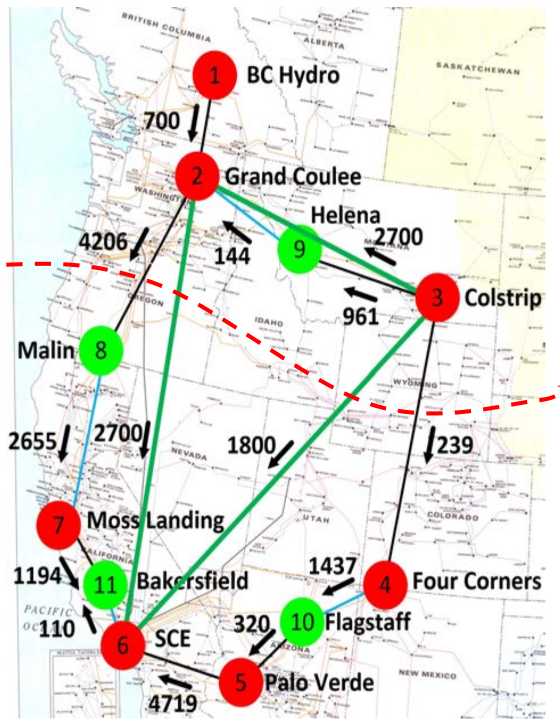
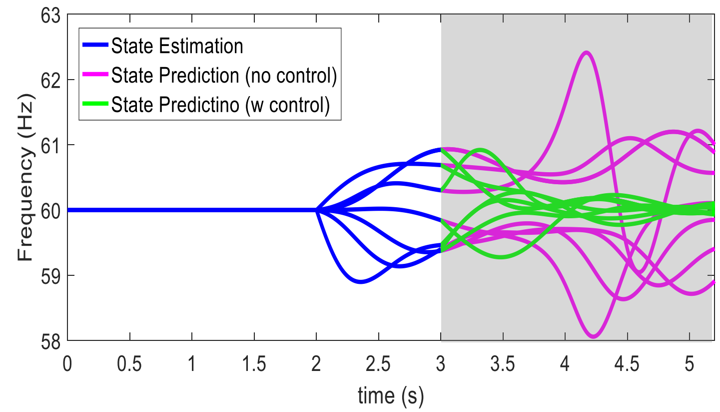
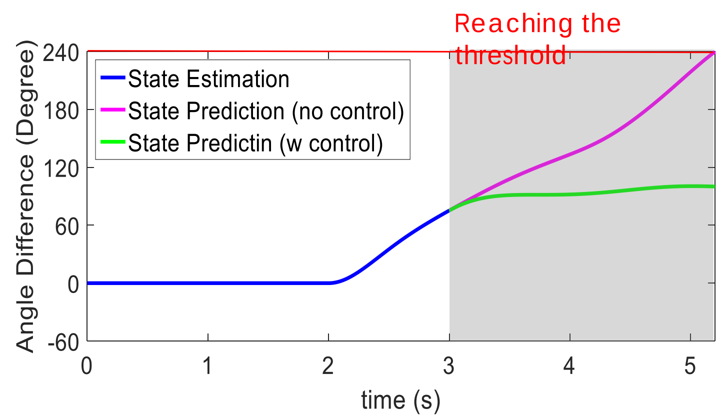
HTB Demo Scenario – State Prediction and Control to Prevent Transient Instability

Using a State Predictor for proactive, controlled separation against transient instability:

- Based on real-time state estimation, the State Predictor calculates generator states semi-analytically for a future time window.
- After a line trip between buses 2 and 8, once the angle difference between G2 and G7 is predicted to reach a threshold, separate the system and stabilize frequencies by HVDC.







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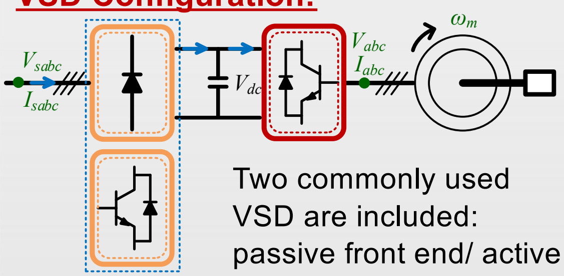
Emulation of Aggregated VSD to Provide Grid Frequency Regulation

- Variable speed drives (VSDs) control motor speed and are increasing in penetration because of the system efficiency gains typically have < 2 year payback.
- Many VSD loads (pumps and fans) can provide frequency regulation service (FRS) by adjusting motors' reference speed temporarily.

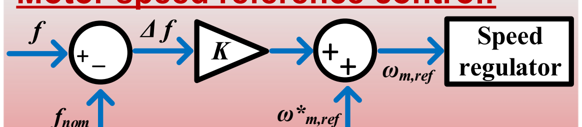
FRS parameter includes activation signal, frequency dead band, K_f, etc.

VSD Configuration:

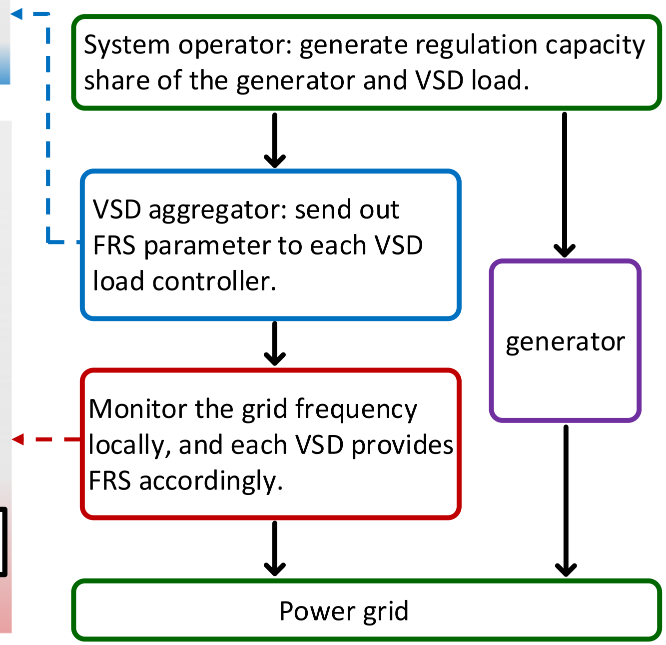


Two commonly used VSD are included: passive front end/ active front end VSD.

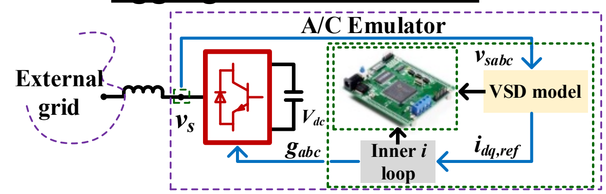
Motor speed reference control:



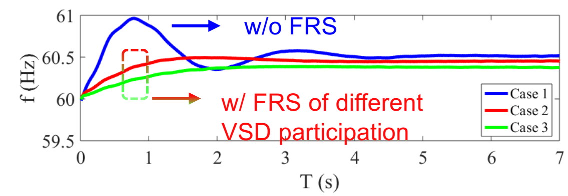
➢ **VSD load FRS process:**

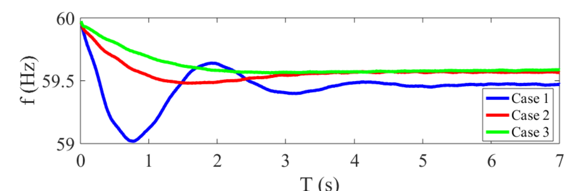


➢ **Power emulator of aggregated VSD model:**



➢ **VSDs provide FRS under grid disturbance:**



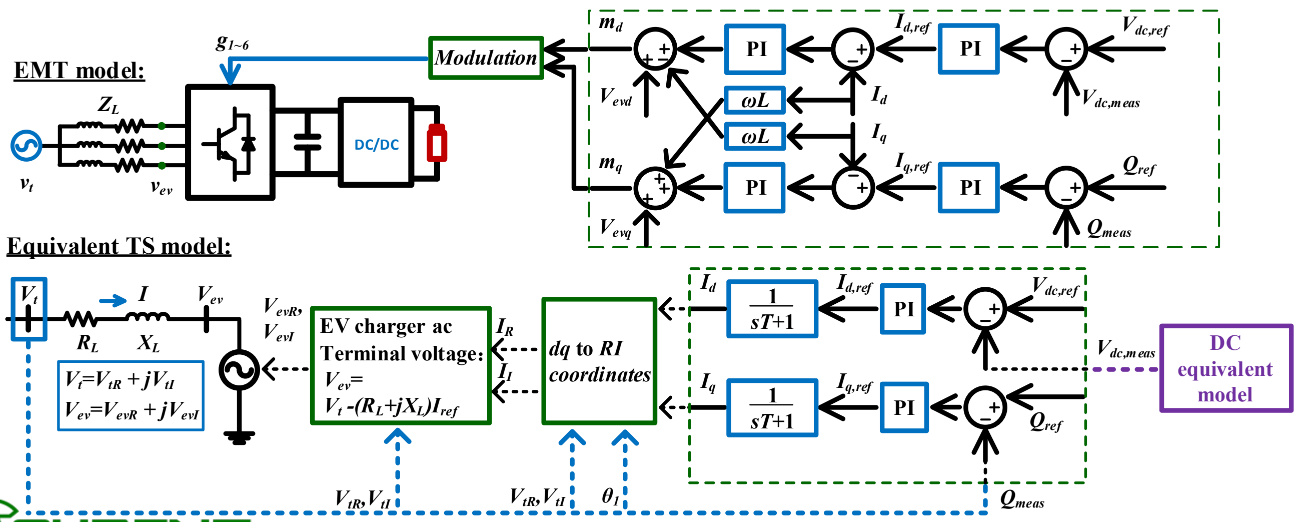


Power Electronics Interfaced Load Modeling in Transient Stability Simulator

- The developed power electronics (PE) interfaced load for transient stability (TS) studies emphasizes electromechanical transients and oscillations in the context of large-scale power network.
- TS model of electric vehicle (EV) charger is created as a typical PE interfaced load. EV charger TS model is suitable for large-scale TS analysis focusing on relatively slow dynamic of PE devices.

➢ **EV charger modeling principle in TS simulator:**

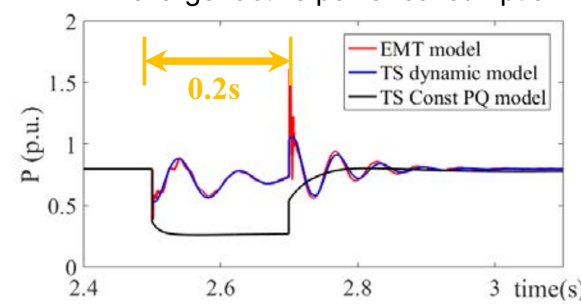
EV charger equivalent TS model is developed based on the detailed electromagnetic transient (EMT) model according to reasonable simplification:



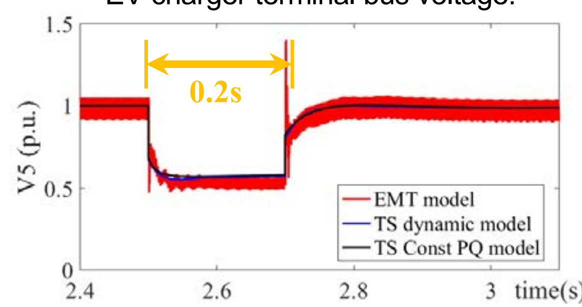
➢ **Model verification: EV charger load subject to terminal bus voltage sag:**

Integrate the EV charger load into IEEE 9 bus system. A significant terminal voltage sag occurs at t = 2.5 s and last for 0.2 s.

EV charger active power consumption:



EV charger terminal bus voltage:



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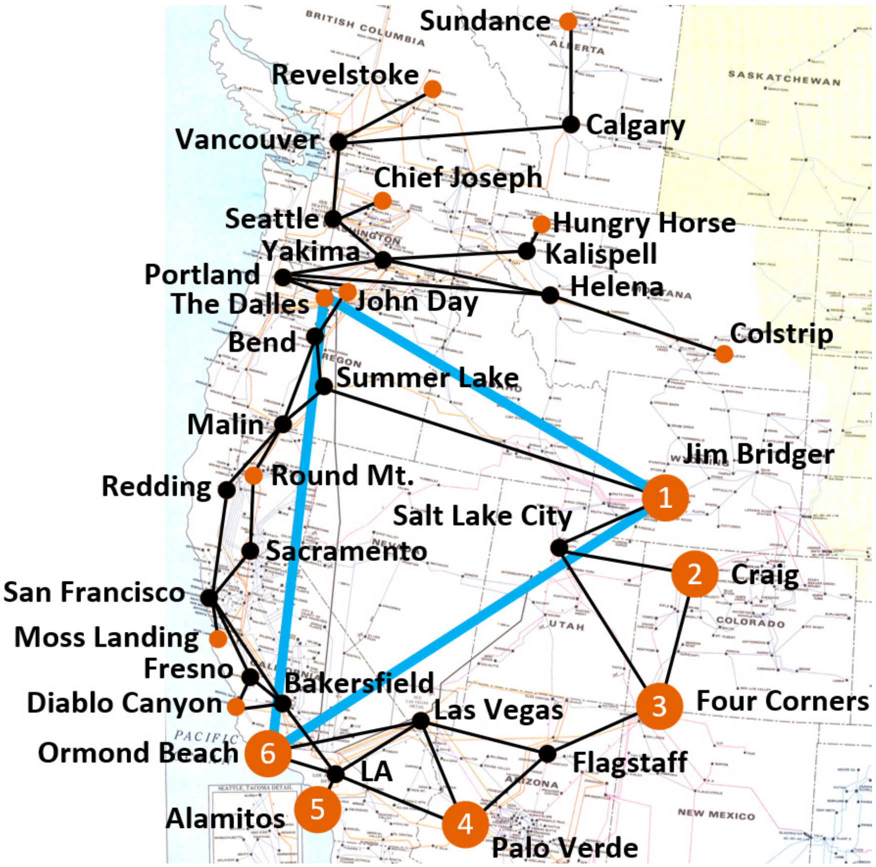
Demo 1: System Security Framework: Stability in Late Afternoon



1. In late afternoon, PV generation is decreasing and other generation rapidly increasing.
2. Trip some generation at LA area, local generation sources are not able to handle the ramping rate of the load
3. Use HVDC to transfer the power from the north to support the load

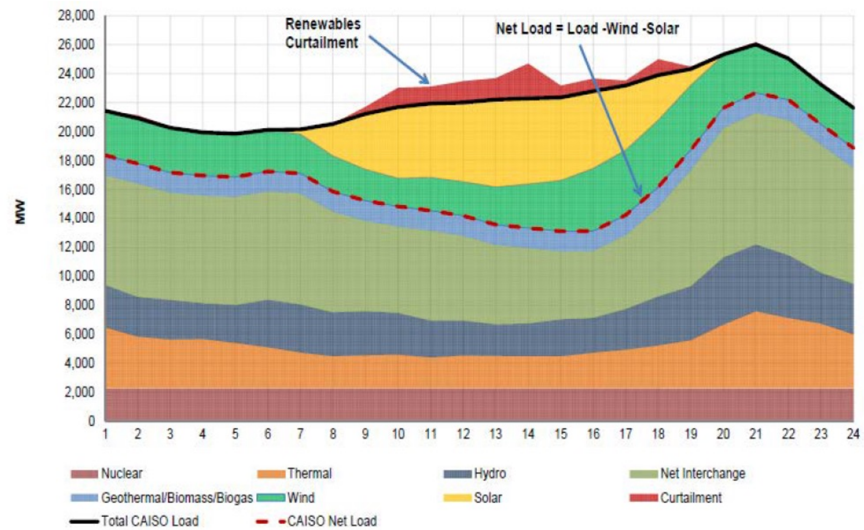
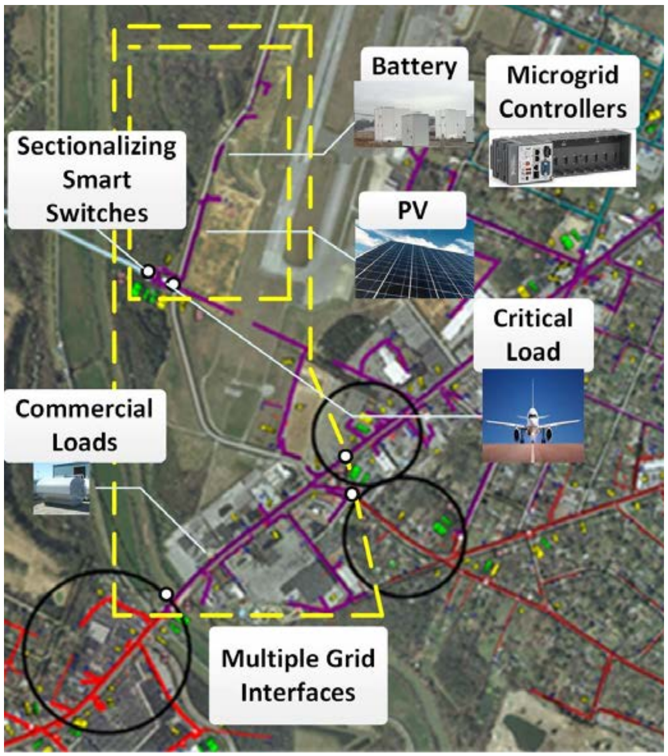


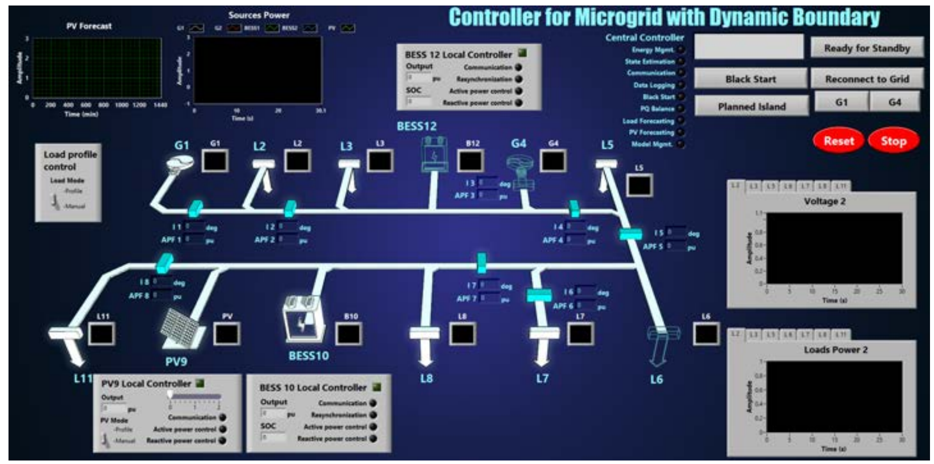
Figure 4. CAISO's generation breakdown for April 24, 2016. ***Illustration from CAISO***

HTB Microgrid Controller Testing

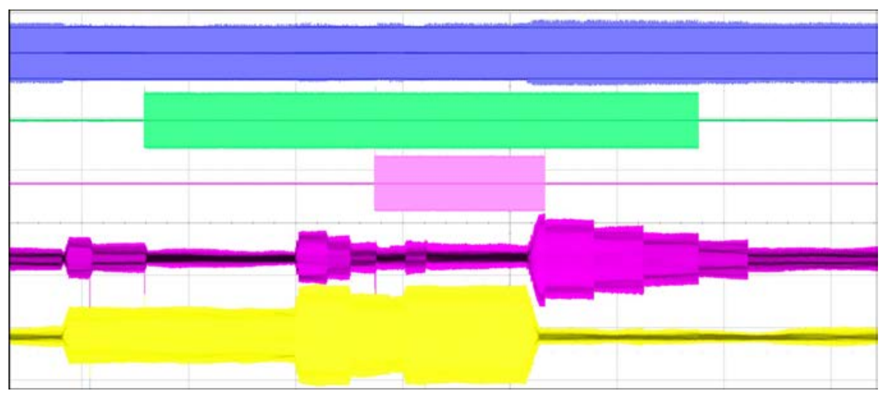
Microgrid with Dynamic Boundary
by Sectionalizing Smart Switches



Controller Interface for HTB Tests



Oscilloscope Measurements of Boundary Change Tests



Battery/PV Voltage

L2 Voltage

L3 Voltage

Battery Current

PV Current

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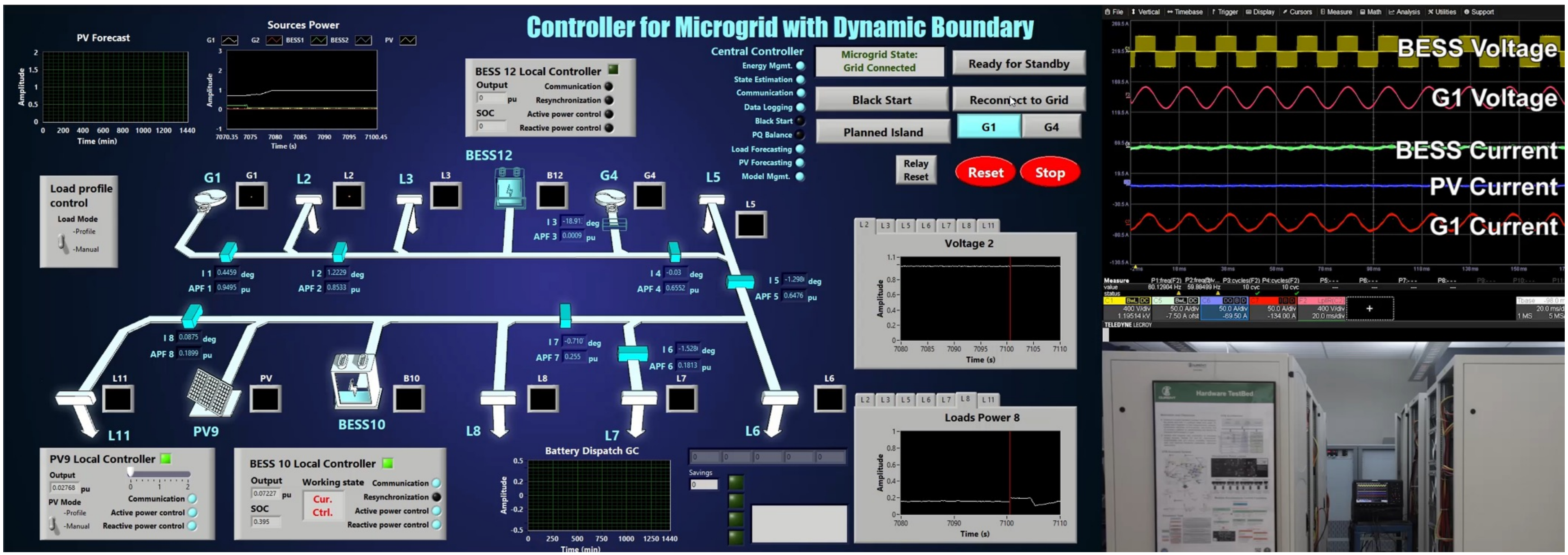
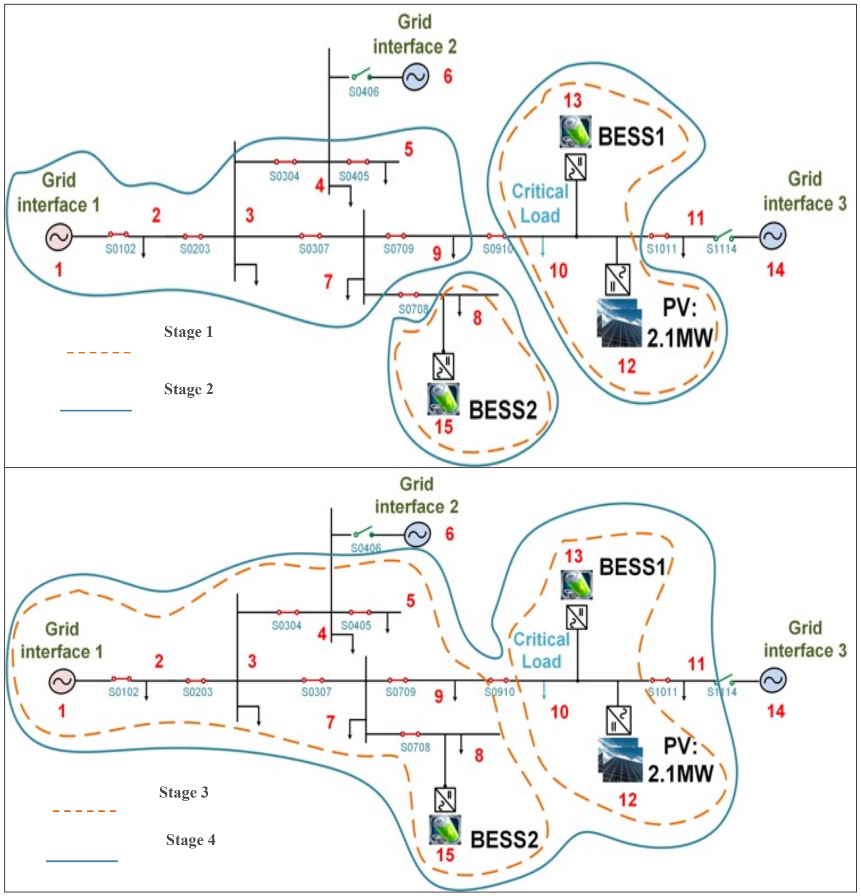
HTB Microgrid Controller Testing

Microgrid with Dynamic Boundary by Sectionalizing Smart Switches



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

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.

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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.

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