Overview of CURENT
Control Architecture for the Future Power Grid

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NSF Engineering Research Centers

- NSF program of focused research on an engineering problem. Among the most significant investments NSF will make in an area with support for up to 10 years.
- Program elements include:
  - Outreach (K-12 education)
  - Research experience for undergraduates
  - Entrepreneurship training
  - Industry program
  - Systems engineering approach
  - International collaboration

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CURENT – NSF/DOE ERC

- One of only two ERCs funded jointly by NSF and DOE. Core budget: ~$4M/year for 5-10 years but highly leveraged to be able to fully support programs.
- CURENT only ERC devoted to wide area controls and one of only two in power systems.
- Partnership across four universities in the US and three international partner schools. Many opportunities for collaboration.
- Expect 50+ industry members to eventually join. Presently have 33 members.
- Center began Aug. 15th 2011

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Why CURENT?

- Energy sustainability is one of the most fundamental societal challenges.
- Changing and uncertain generation mix; reliance on fossil fuels creates significant environmental and national security issues.
- Solutions are being pursued which focus mostly on source and load.
  - Renewable energy sources, mainly wind and solar
  - Electric vehicles and energy storage
  - Energy efficient lighting, appliances, and buildings

These solutions require a fundamentally new approach to electric delivery

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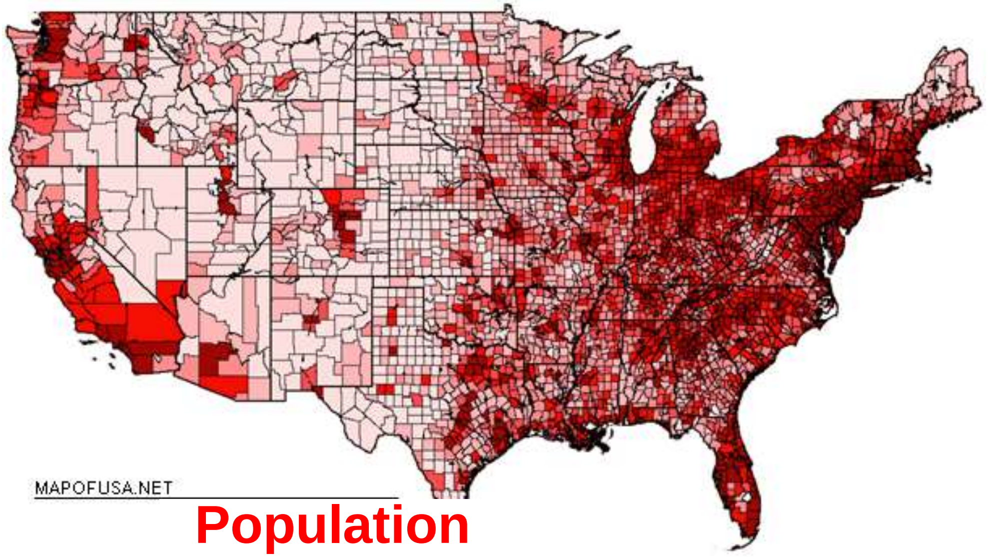
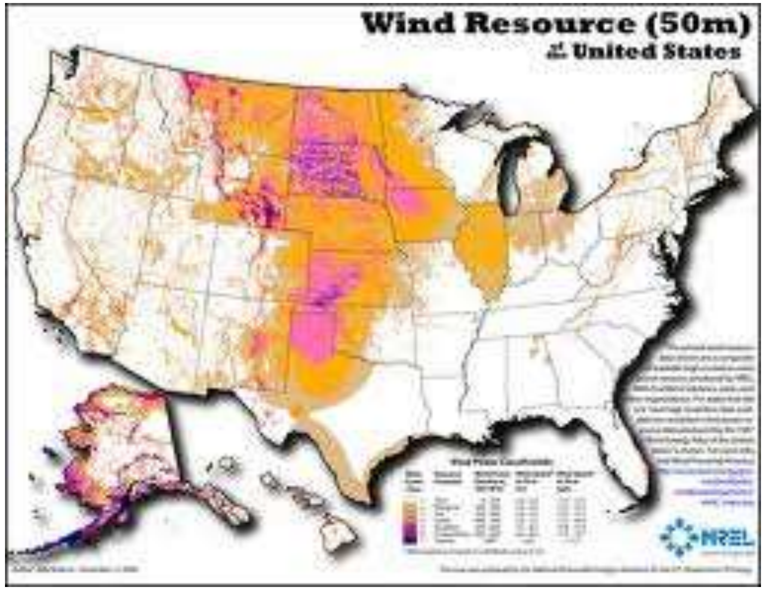
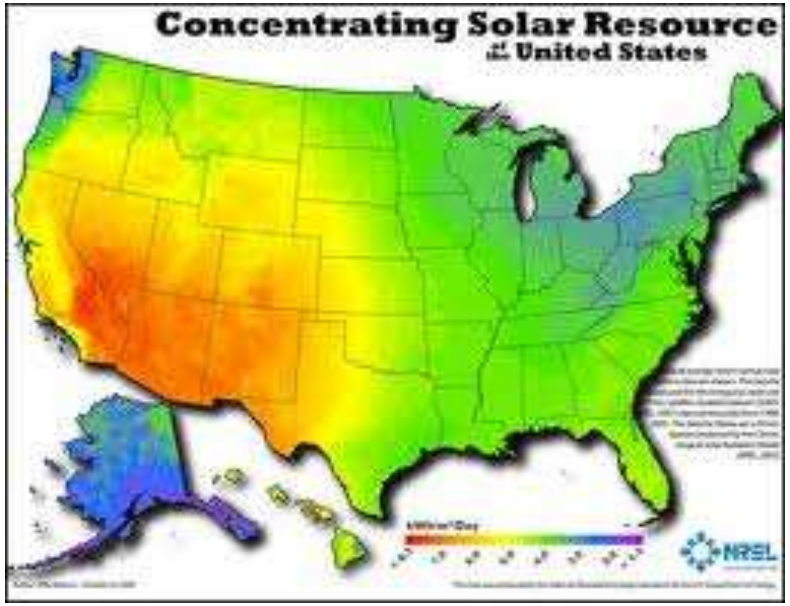
US Wind and Solar Resources



Population



Wind



Solar

Best wind and solar sources are far from load centers.

Transmission networks must play a central role in integration.

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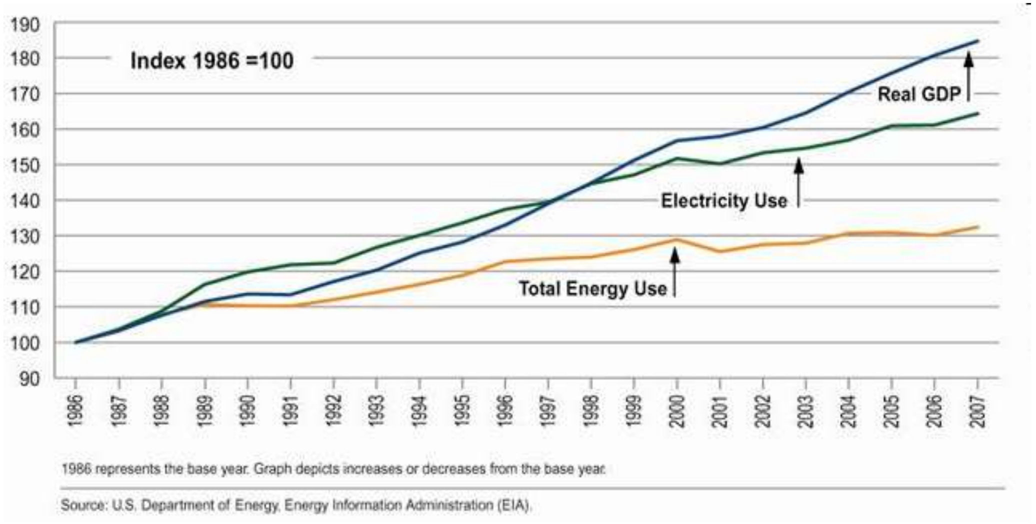
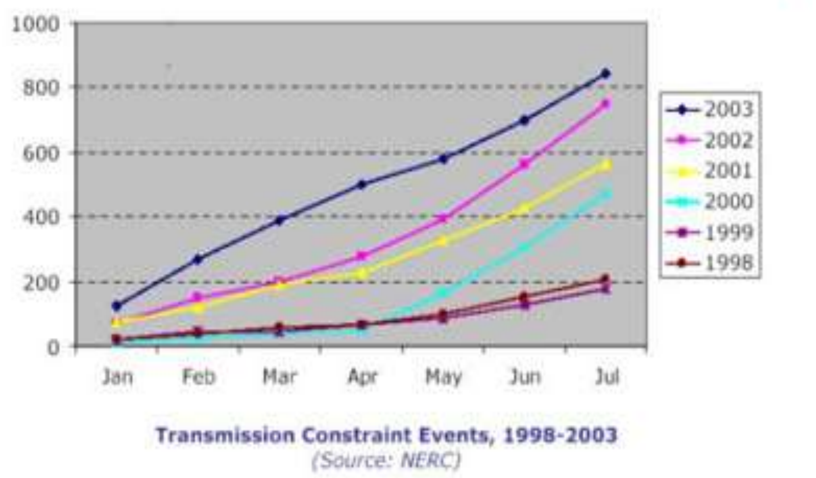
http://www.eia.doe.gov/cneaf/solar.renewables/ilands/fig12.html

Aging Infrastructure

Growth in electricity consumption



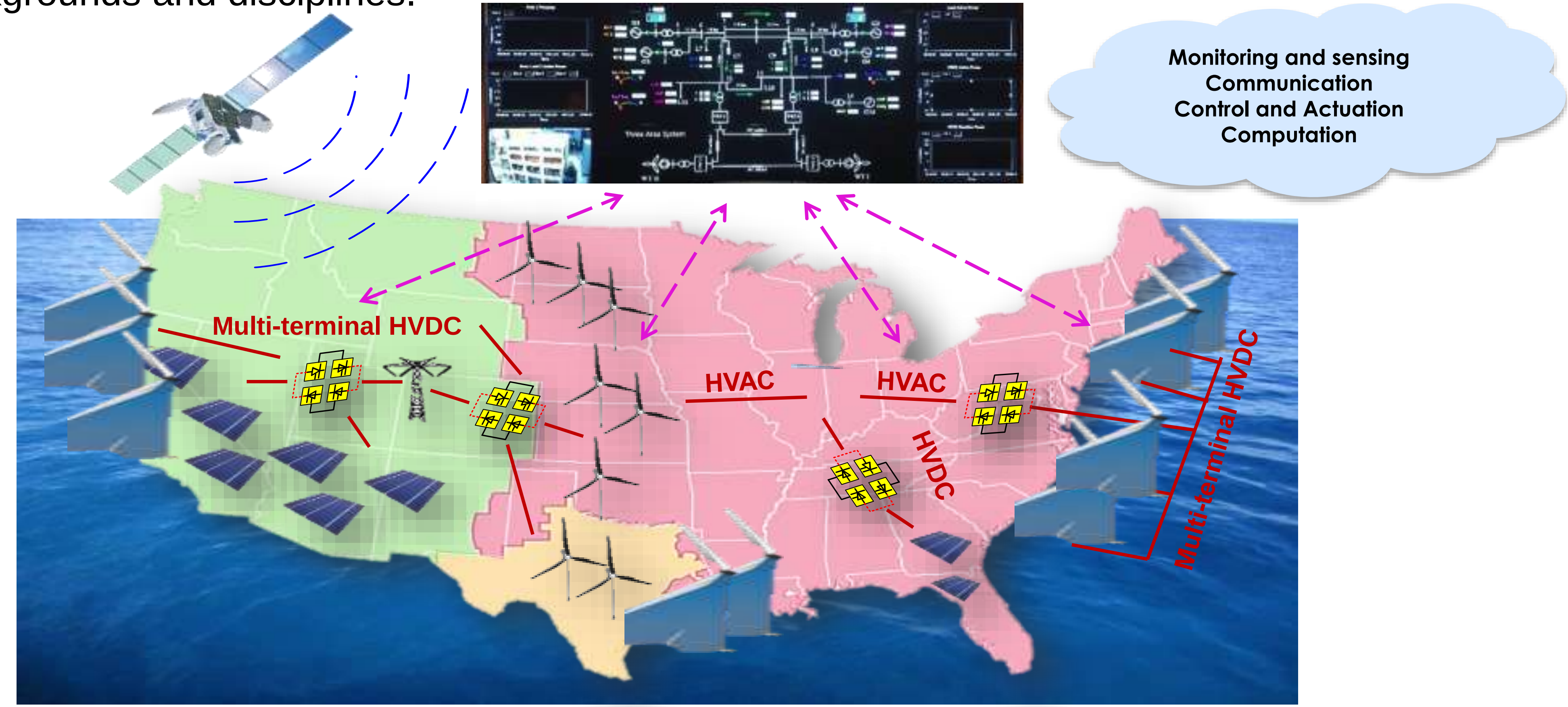
Transmission constraint events



- Transmission investment has lagged generation investment and led to several bottlenecks in the Eastern interconnect and Western interconnect.
- Limited transmission impacting reliability and cost, preventing full use of renewables

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 and disciplines.



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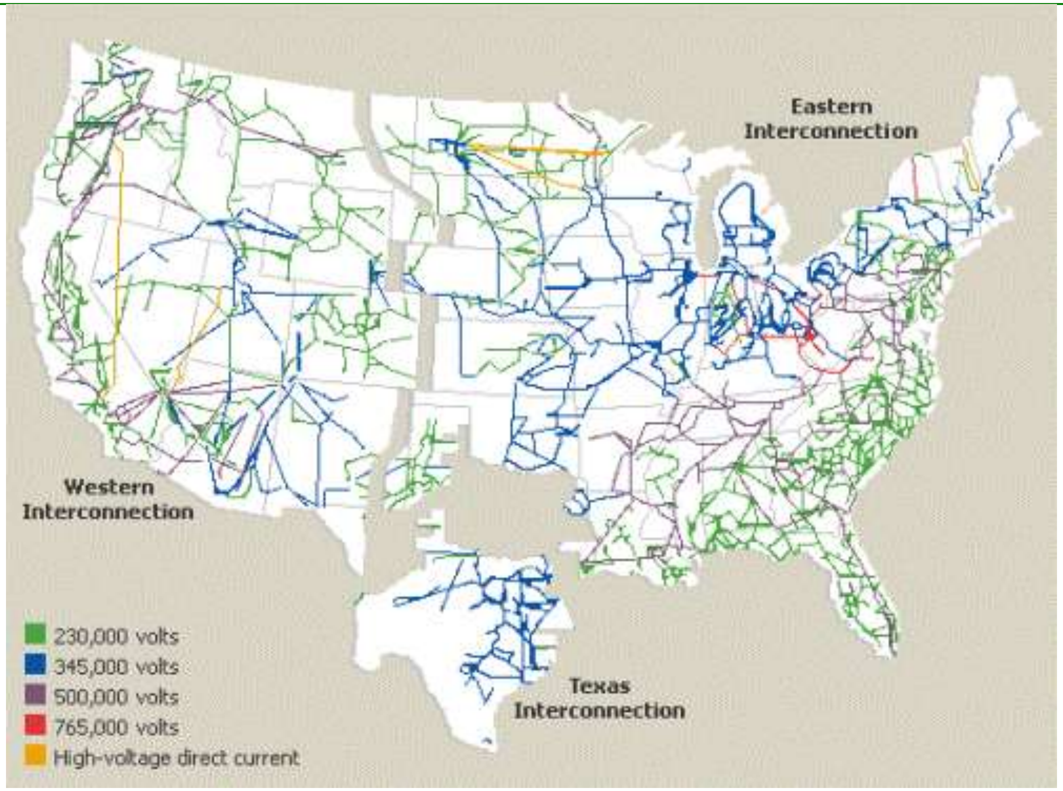
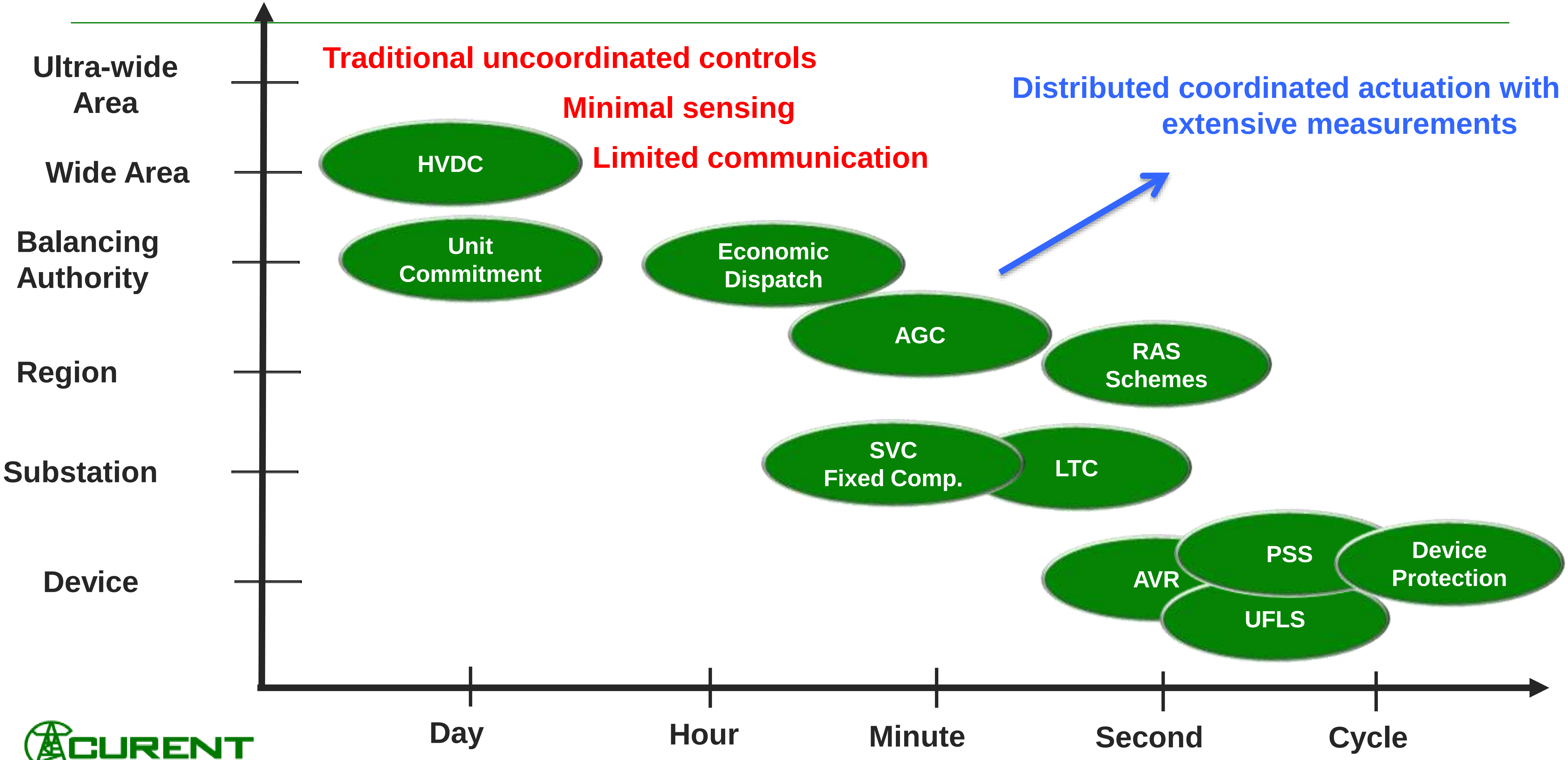
CURENT Engineered System

Today's System



- Low penetration of renewable energy sources
- Dominated by inflexible AC transmissions; large capacity margin
- Load variability only; generation following load
- Limited situational awareness; mostly local control

Today's Operations
Some wide area and some fast but not both

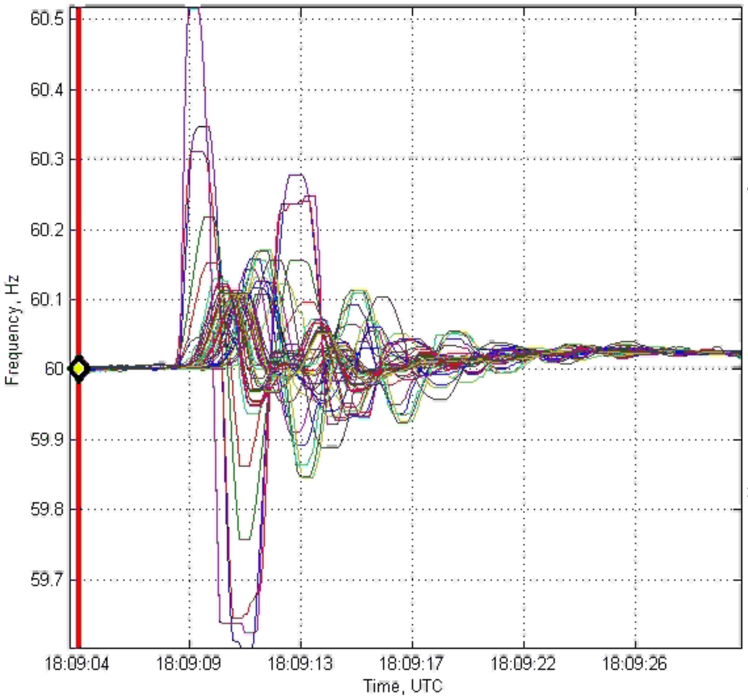


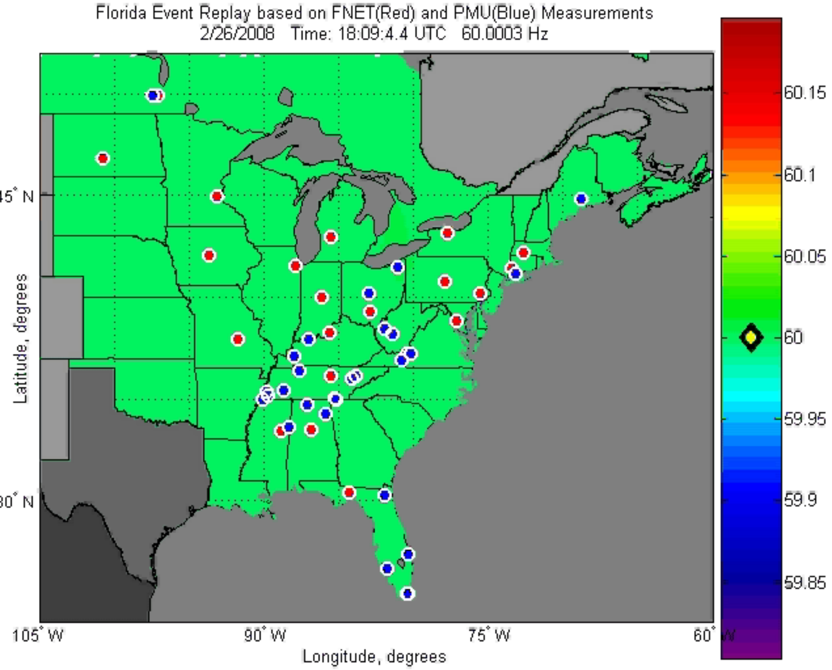
Wide Area Measurement

Unique Capabilities: UWA real-time grid monitoring system at UTK – Yilu Liu

FDR Sensor

FNET Monitors in the Field





Today's Control/Actuation and Protection

- Generator controls
  - Voltage regulation – AVR
  - Power system stabilizer – PSS
  - Automatic generator control – AGC
  - Fast valving, dynamic braking
  - Tripping of units
- Transmission
  - Switched capacitors and reactors
  - HVDC, STATCOM, SVC and FACTS (all limited)
- Load and distribution controls
  - Switching
  - Shedding for large customers or substations
  - Limited voltage (mostly open loop or timed)
- Protection
  - Over-current
  - Differential
  - Out of step
  - Pilot relaying
  - Special protection systems and remedial action schemes
- System controls
  - Unit commitment
  - Economic dispatch (OPF)
  - Voltage scheduling
  - Load following

➔ Mostly local and if non-local probably not closed loop

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Today's Monitoring and Communications

- Communications
  - SCADA via remote terminal units – polled 2-4 seconds; sent to control center
  - Point-to-point – some pilot relaying; SPS and RAS (all fixed)
  - Smart metering and distribution SCADA (still limited)
- Monitoring
  - Transmission systems - voltages and currents at higher voltages, status of lines
  - Some voltages and currents at lower voltages
  - Substations – status, voltages, currents, relatively few PMU units (but rapidly growing), substation batteries, fault recorders, etc. Many variables not available to control center.
  - Distribution systems – some status, very few other variables (but this is changing)
  - Weather, water conditions, etc., – not well integrated into EMS

➔ Generally inflexible, limited in scope and variables monitored

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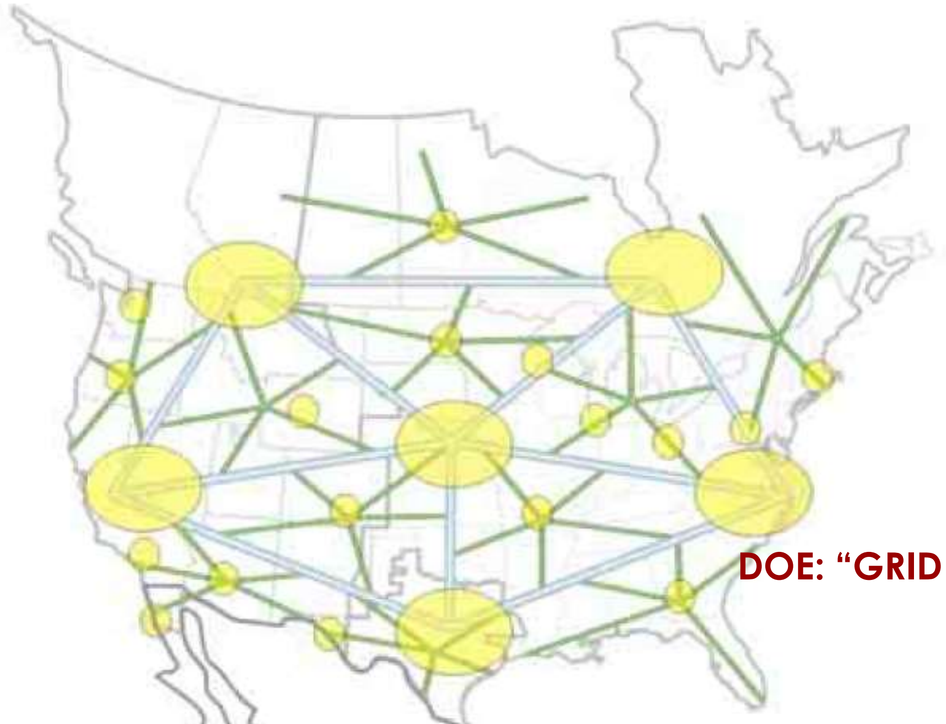
CURENT Engineered System

Future System



Electricity Backbone, Regional Interconnection, Plus Local Distribution, Mini- and Micro-Grids

DOE: "GRID 2030" VISION

- **High penetration of renewable energy sources (>50%)**
- **Flexible DC and AC transmissions with small (~0) margin**
- **Load and source variability; responsive load**
- **High situational awareness; ultra-wide-area control**

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Possible Future Control/Actuation and Protection

- Generator controls
  - Contextual – supportive of global state of system
  - Variable breakdown along time domain and phenomena (voltage, frequency) dependent on device
  - Greater diversity of controls with associated with different unit types
- Transmission
  - Pervasive electronics via HVDC, STATCOM, SVC and FACTS
  - Other devices?
- Load and distribution controls
  - Selective load shedding and scheduling
  - Voltage scheduling for improved efficiency and security
- Protection
  - New schemes to support overall system operation
  - PMU based
- System controls
  - Shorter time frame for scheduling (perhaps 5 minutes)
  - Tertiary voltage control
  - Frequency control replaced by phasor tracking

➔ Still have local controls but guided by system and closed loop

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Possible Future Monitoring and Communications

- Communications
  - SCADA gathers raw sampled data
  - Information routing (e.g., publisher-subscriber model)
  - Pervasive smart meters and distribution SCADA
- Monitoring
  - Transmission systems – line sag, temperature
  - Voltages and currents at lower voltages, some PMU
  - Complete substation available to control center
  - Detailed weather and other event information integrated into EMS

➔ Generally flexible, broad in scope and many variables monitored

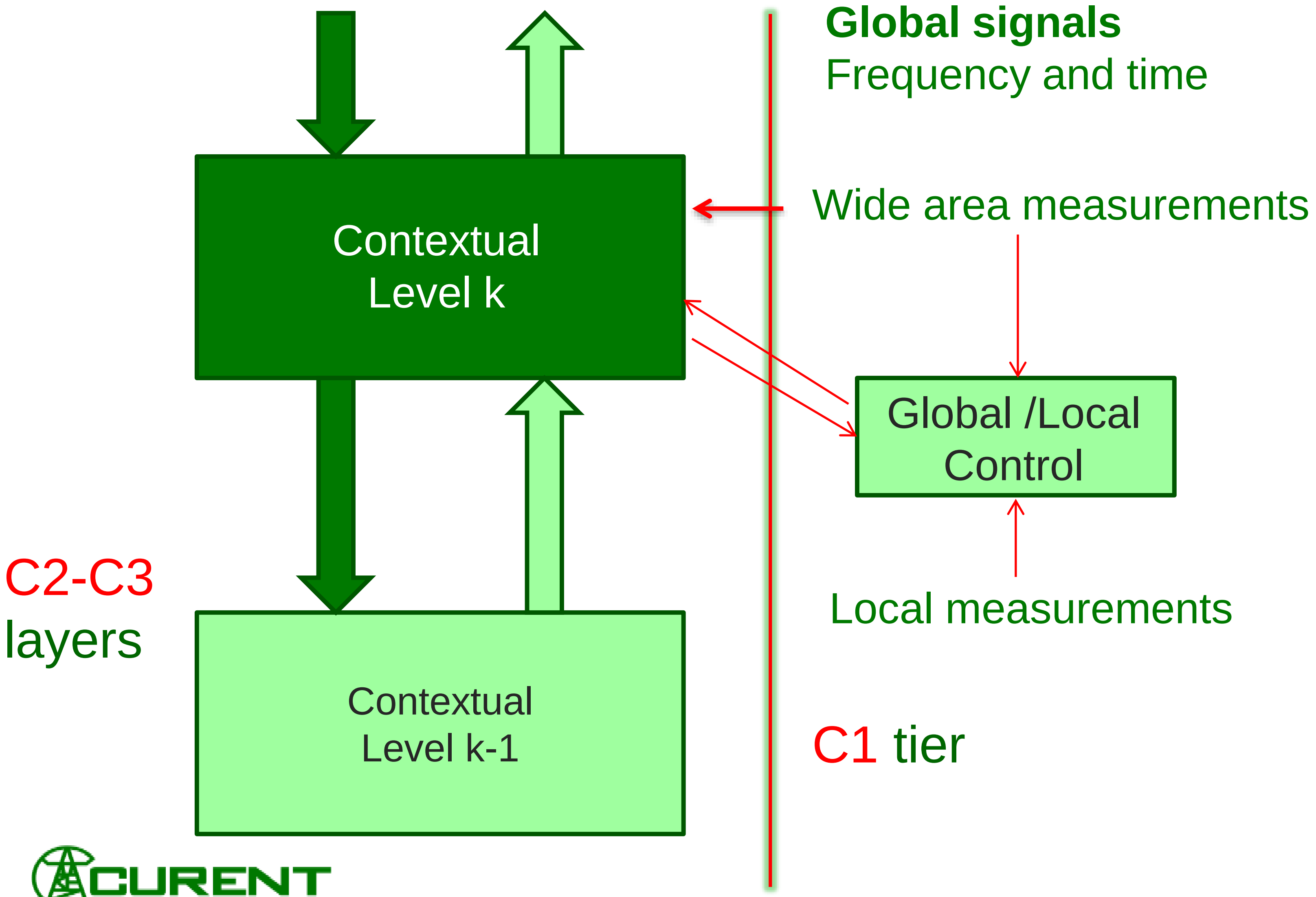
Major Research Questions

Future Control Architecture

- Information flow
  - What information is needed where?
  - How much latency can be tolerated?
  - Trade-off – more information leads to better decisions but slower response
- Control architecture
  - Do all devices contribute to control?
  - For which phenomena do devices contribute (some fast and some slow)?
  - How much contribution is needed to ensure performance?
  - Trade-off – more devices contributing properly expands viable operating region but requires greater sophistication and cost
- Economics and optimization
  - What functionality should come from markets and what by regulation?
  - Contributions from certain devices are more cost effective
  - Trade-off – greater optimization leads to lower cost but requires more voluntary sharing of information and but some services may not lend themselves to an efficient market structure

➔ Design needs to be a series of trade-offs between communication needs, device sophistication, resiliency, speed of response, economic performance and device reliability vs. system reliability.

CURENT Control and Coordination Architecture

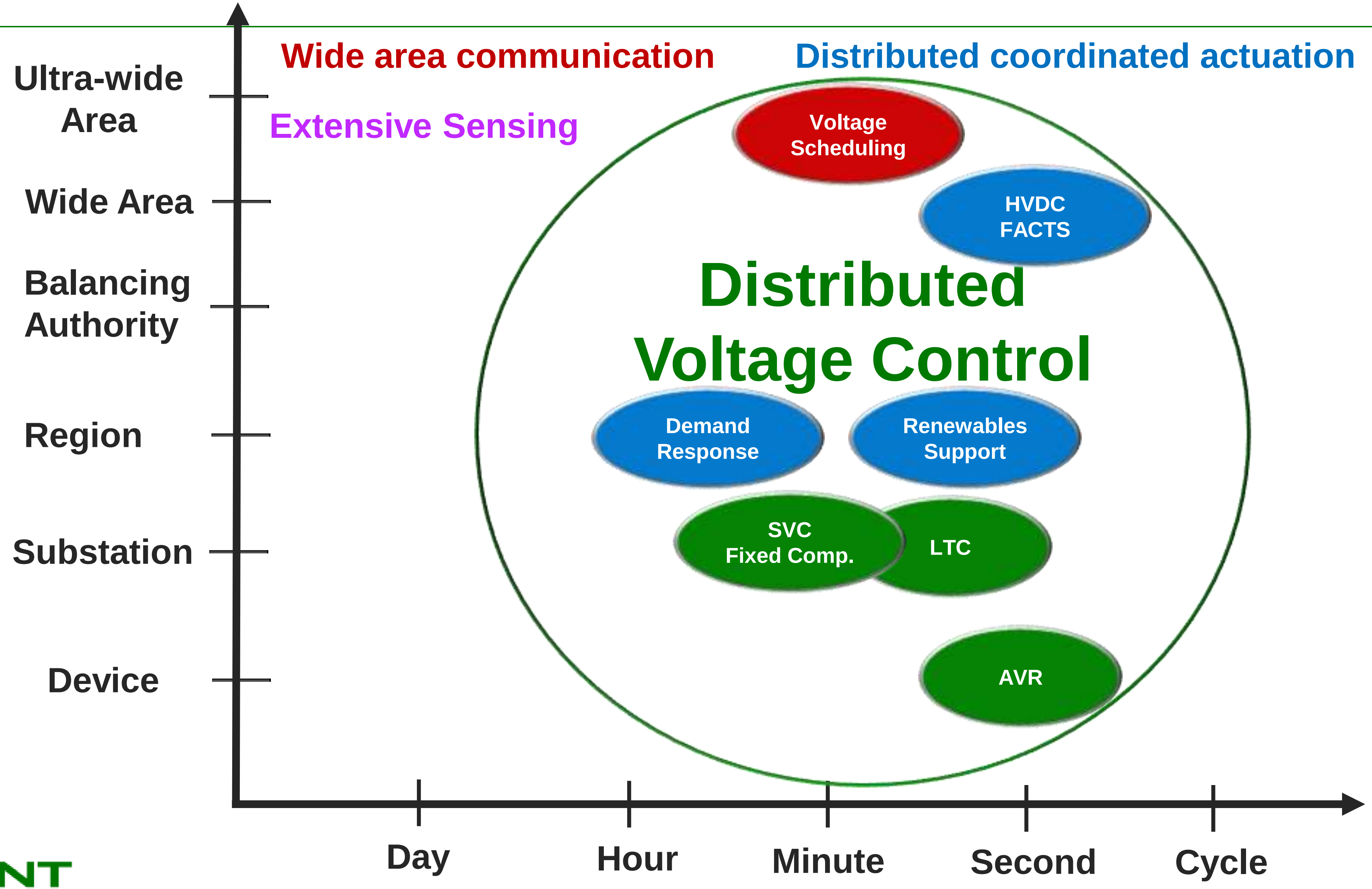


Resilience and scalability by

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

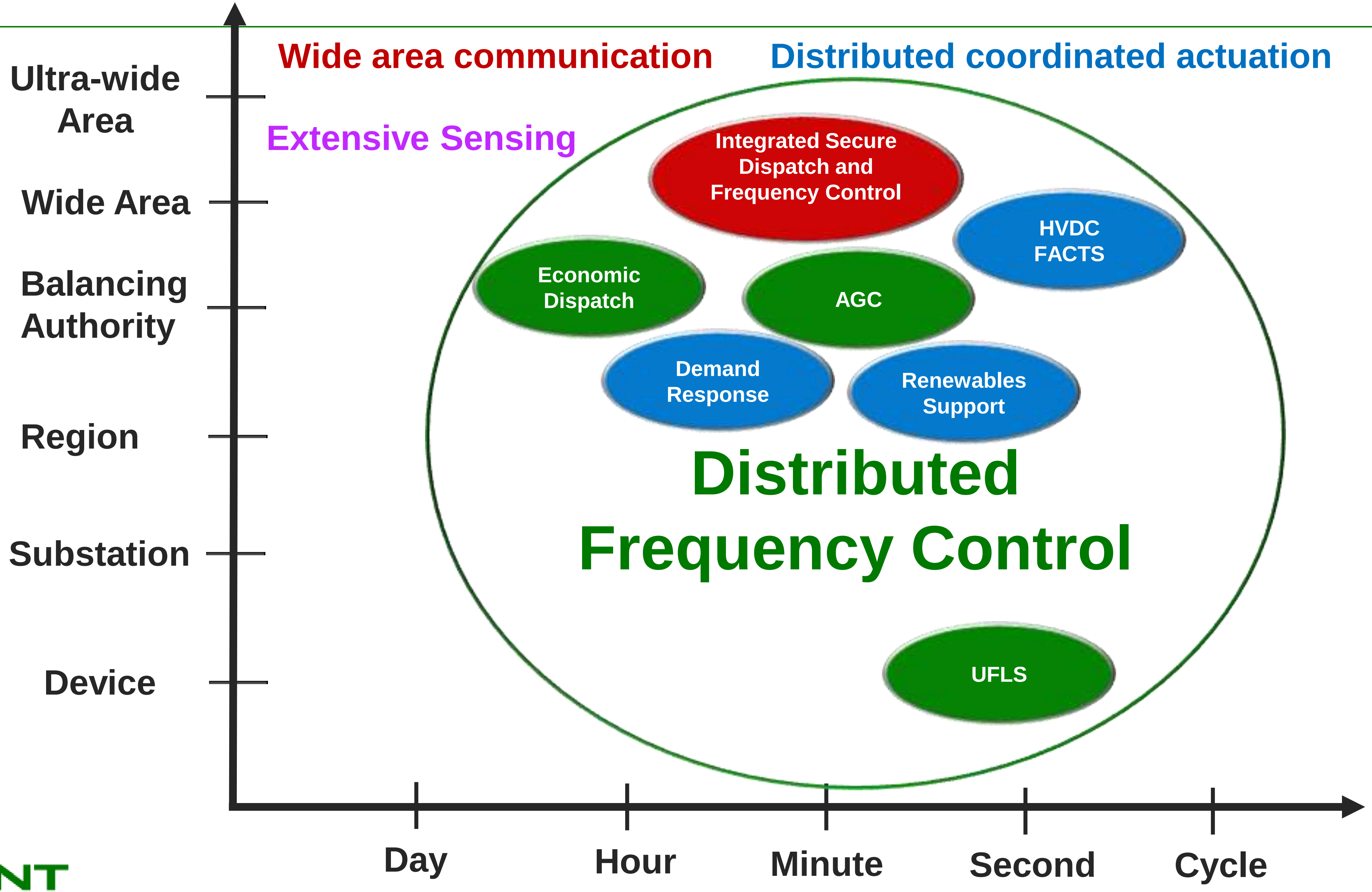
Voltage Control

Wide area with distributed actuation



Frequency Control

Wide area with distributed actuation



Example Value of Improved Controls

Northwest Pacific Intertie

- Two 500kV AC lines and +/- 400kV DC line
  - Designed for transfer of 2000 MW AC and 1440 MW DC
  - Actual capacity was 1300 MW AC due to instability caused by AVRs
  - Power system stabilizers allowed increase to 1800 MW AC
  - Dynamic brake added at Chief Joe allowed up to 2500 MW AC
- Transmission upgrade – third AC line and DC upgrades
  - AC capacity today about 4800 MW (primarily voltage)
  - DC capacity today about 3000 MW

➔ 1990s work by DOE and BPA on WAMS and WACS a direct result of this type of need for improved controls.

Evolution of CURENT System

Generation 1

- Regional grids with reduced order models
- 20% renewable (wind, solar)
- Grid architecture includes HVDC trunk lines, at least one multi-terminal DC grid for off-shore wind farm
- Sufficient monitoring to provide measurements for full network observability
- Closed-loop non-local frequency and voltage control using PMU measurements
- Renewable energy sources and responsive loads to participate in frequency and voltage control

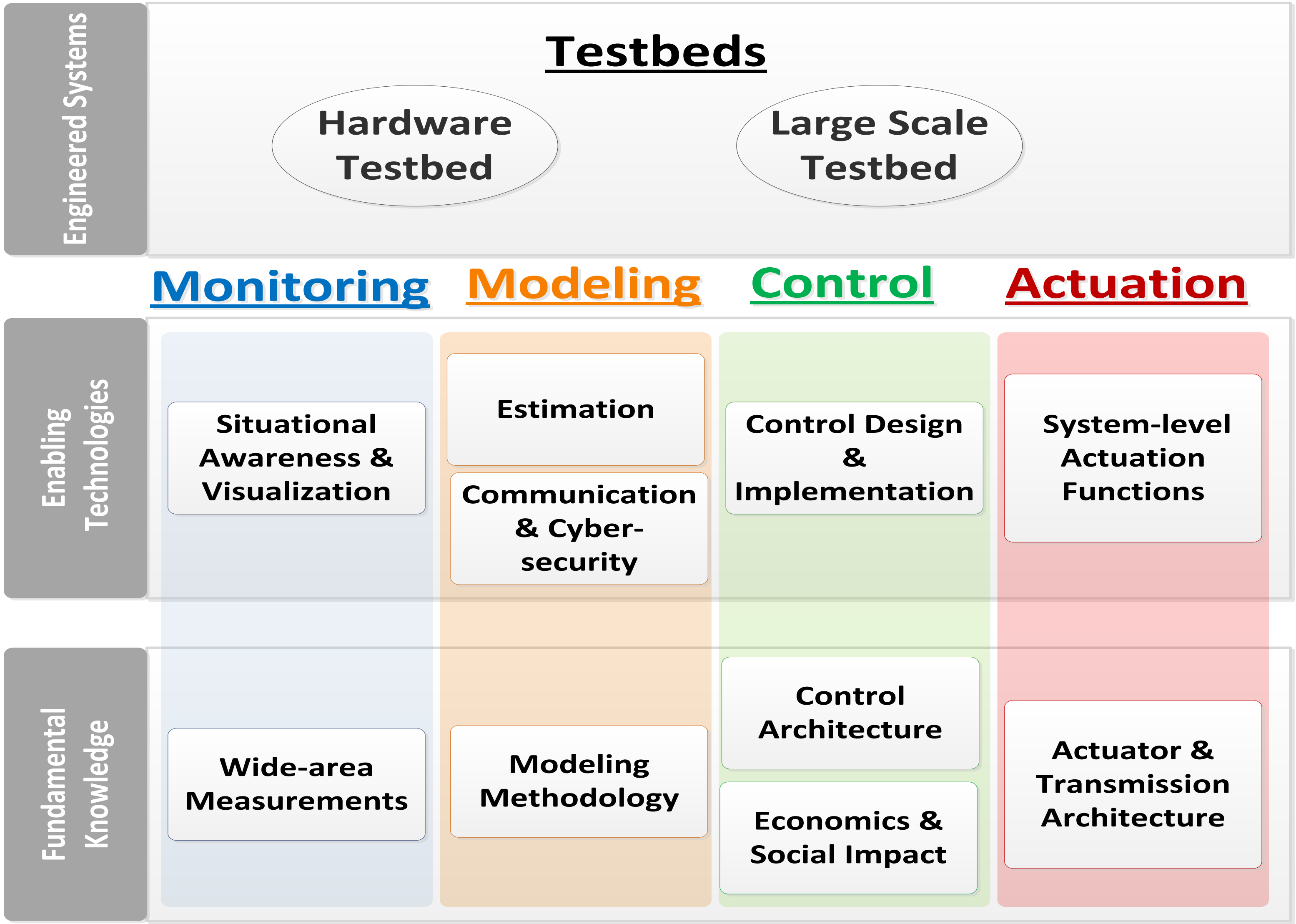
Generation 2

- Reduced interconnected EI, WECC and ERCOT system
- >50% renewable (wind, solar) and balance of other clean energy sources (hydro, gas, nuclear)
- Grid architecture includes UHV DC trunk lines connecting with regional multi-terminal DC grids, and power flow controllers
- Full PMU monitoring at transmission level with some monitoring of loads
- Fully integrated PMU based closed-loop frequency, voltage and oscillation damping control systems, and adaptive RAS schemes

Generation 3

- Fully integrated North American system, with >50% renewable
- Grid architecture includes UHV DC super-grid and interconnecting AC overlay
- Future load composition (converters, EVs, responsive loads), selective energy storage (including concentrated solar with thermal energy storage)
- Fully monitored at transmission level. Extensive monitoring of loads in distribution system
- Closed loop control using wide area monitoring across all time scales and demonstrating full use of transmission capacity
- Coordinated renewable energy source control over wide area for minimum reserves

Three-plane Diagram



Barriers

- System complexity
- Model validity
- Multi-scale
- Inter-operability

Barriers

- Poor measurement design
- Cyber security
- Actuation & control limitation

- *Barriers*
- Lack of wide-area control schemes
- Measurement latency
- Inflexible transmission systems

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CURENT Testbeds:

- **Hardware Testbed**
  - *All Converter -based Reconfigurable Grid Emulator*
    Hardware Emulation of grid clustering with real measurement, communication, and control.

- **Large-scale Testbed**
  - *Virtual Grid Simulator + Future EMCS*
    Real time software platform continuously emulating grid operations
  - *US Grid Model Development and Applications*

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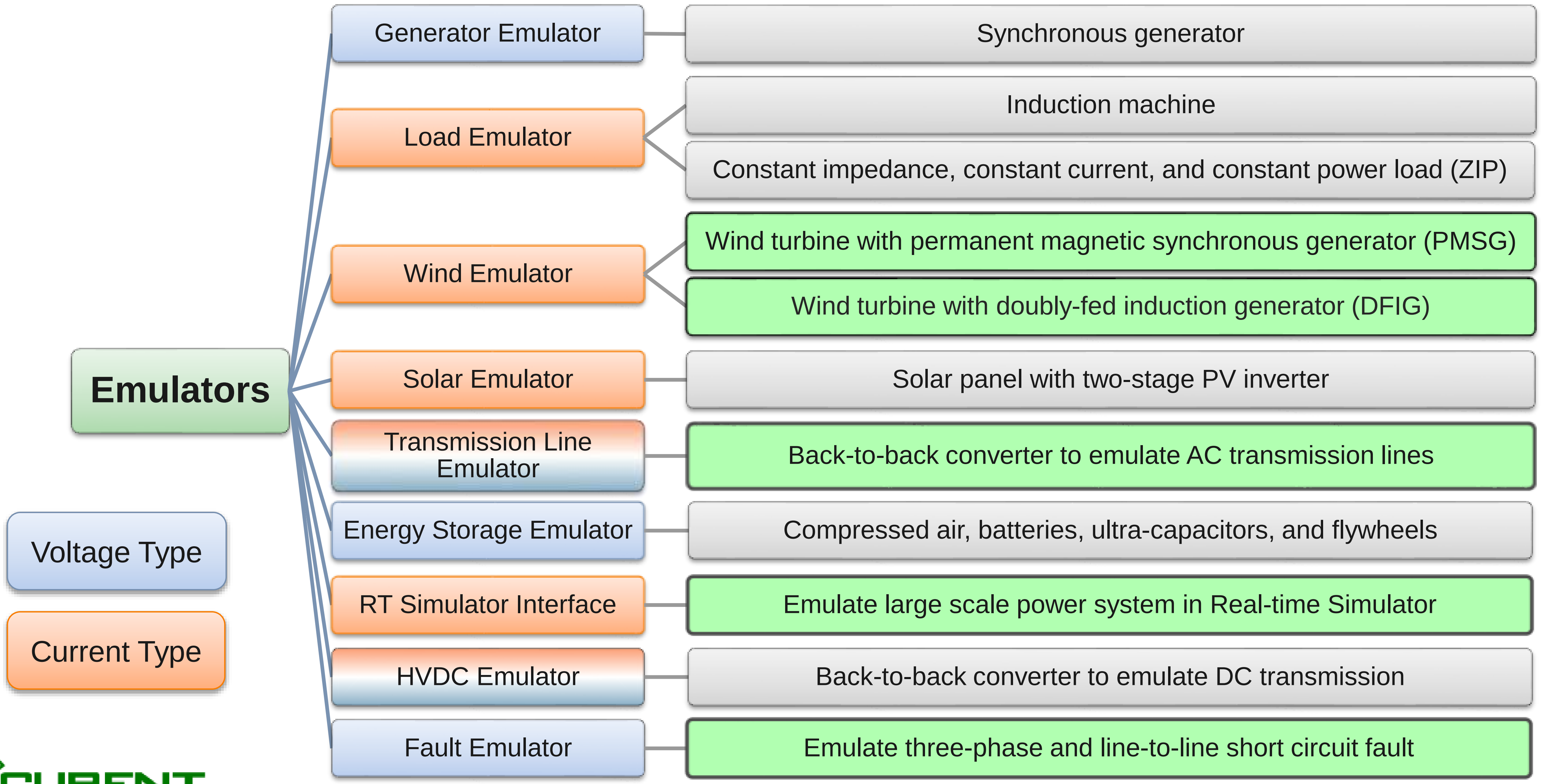
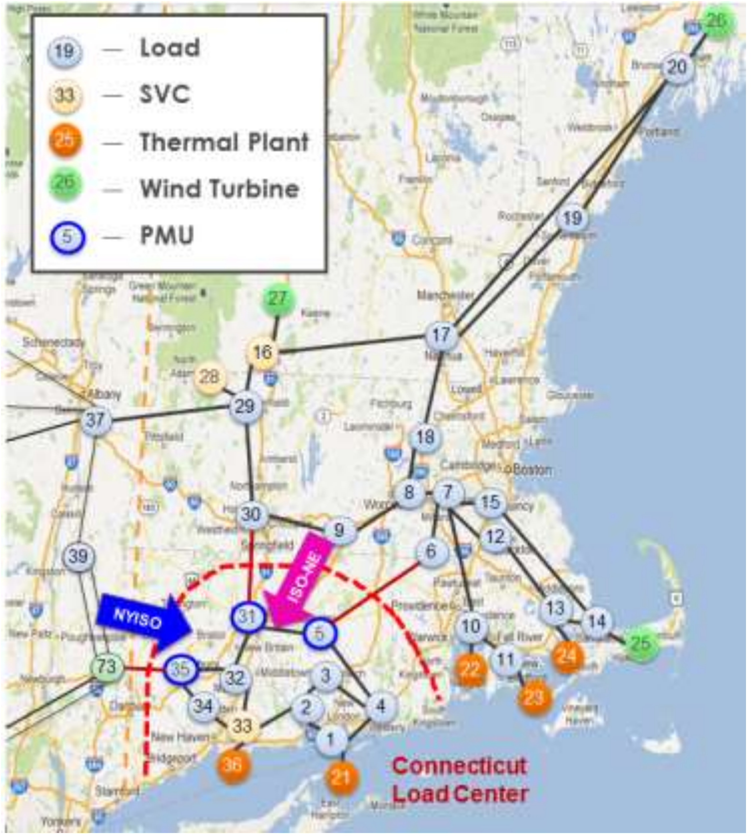
Hardware Testbed

100% Converter-based Grid Emulator

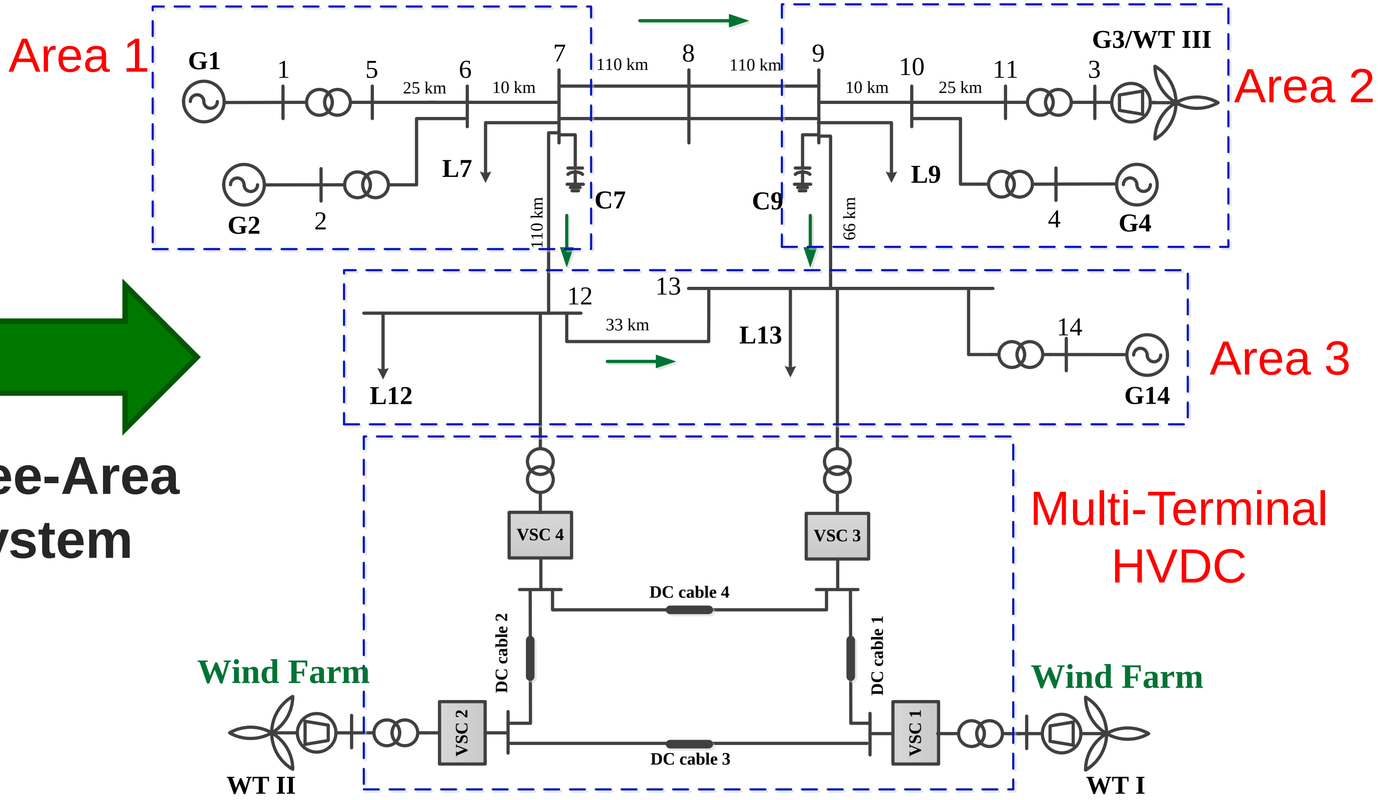
Development of the Emulators in HTB



Hardware Testbed (HTB): Power Converter-based Reconfigurable Grid Emulator



Three-Area System



- Emulated various grid scenarios with interconnected clusters of scaled-down generators, loads, and energy storage.

Industry members: Vacon, National Instruments, Tektronix

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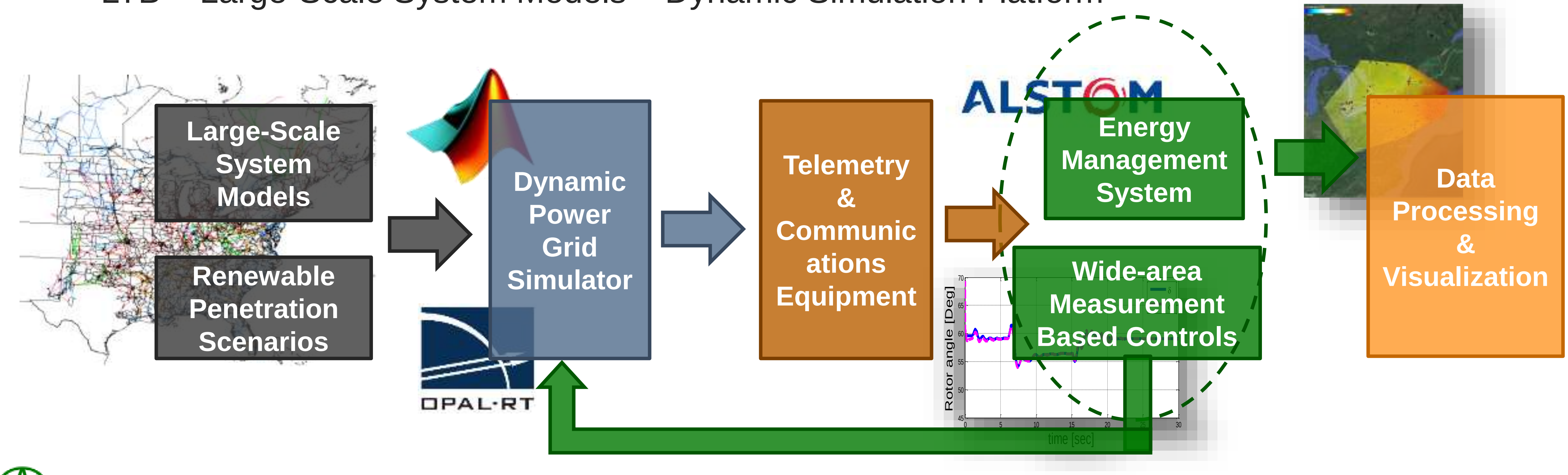
Large-scale Testbed

- Large-Scale Testbed (LTB) is a platform running large-scale dynamic grid models of the future, such as that of North America, with energy management, monitoring, communication, control and visualization capabilities to demonstrate developed technologies and identify needed research directions
- LTB = Large-Scale System Models + Dynamic Simulation Platform



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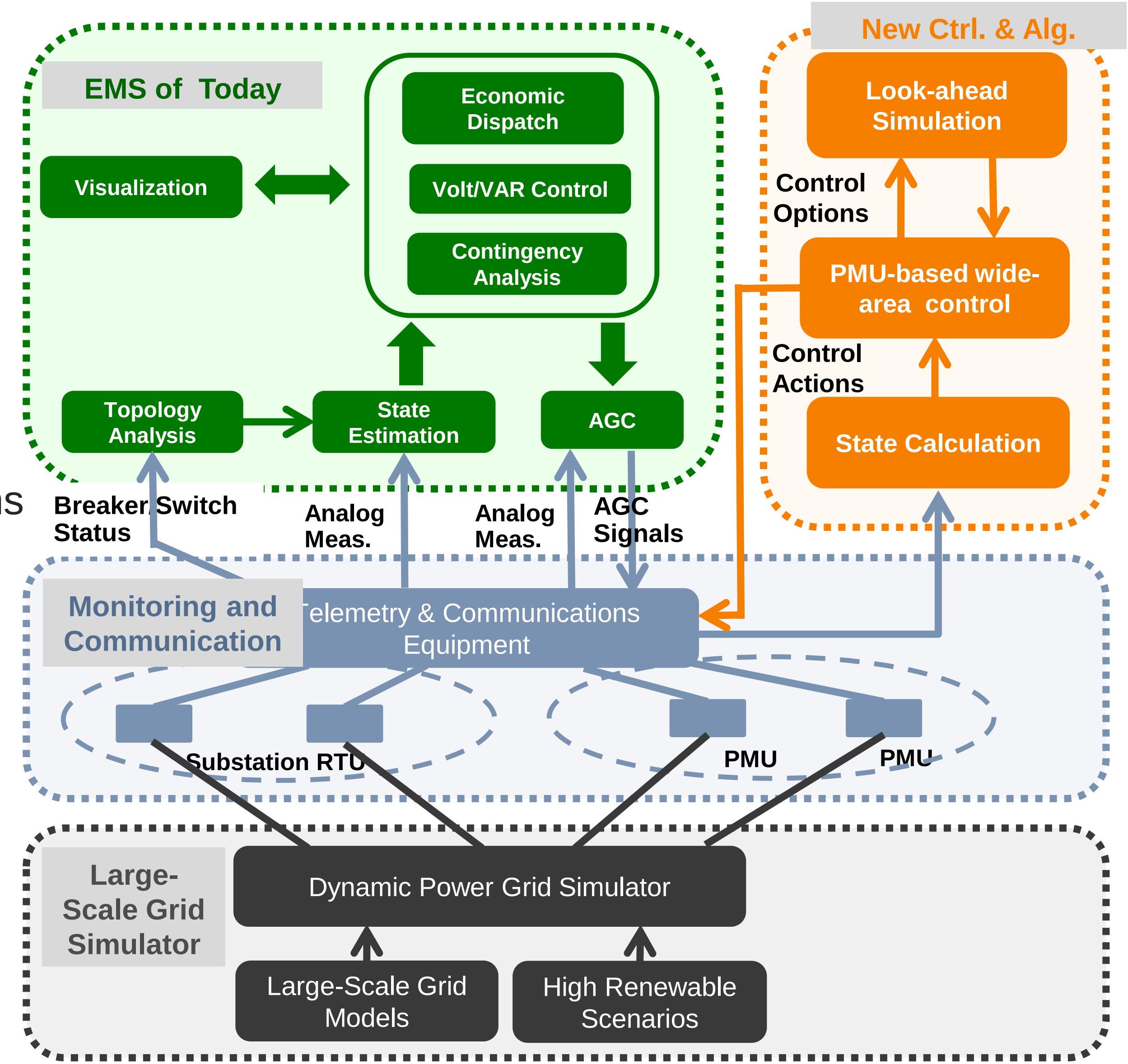
LTB Technical Details

- **Large-scale model complexity**
  - Reduced models for WECC, EI and ERCOT systems
  - 928-bus North America power grid model with dynamics and HVDC
  - Verified models from measurement data
  - 50% Wind penetration scenarios ready
- **Inter-operability**
  - Decoupled architecture using streaming
  - Quick integration of new controls and algorithms
  - Easy to swap in modules (simulator, EMS and controls)
- **Measurement-based control and applications**
  - Simulate 30 Hz PMU sampling
  - Dynamic 2-stage state estimator
  - Measurement-based voltage stability index
  - Islanding control
  - Wide-area AGC control



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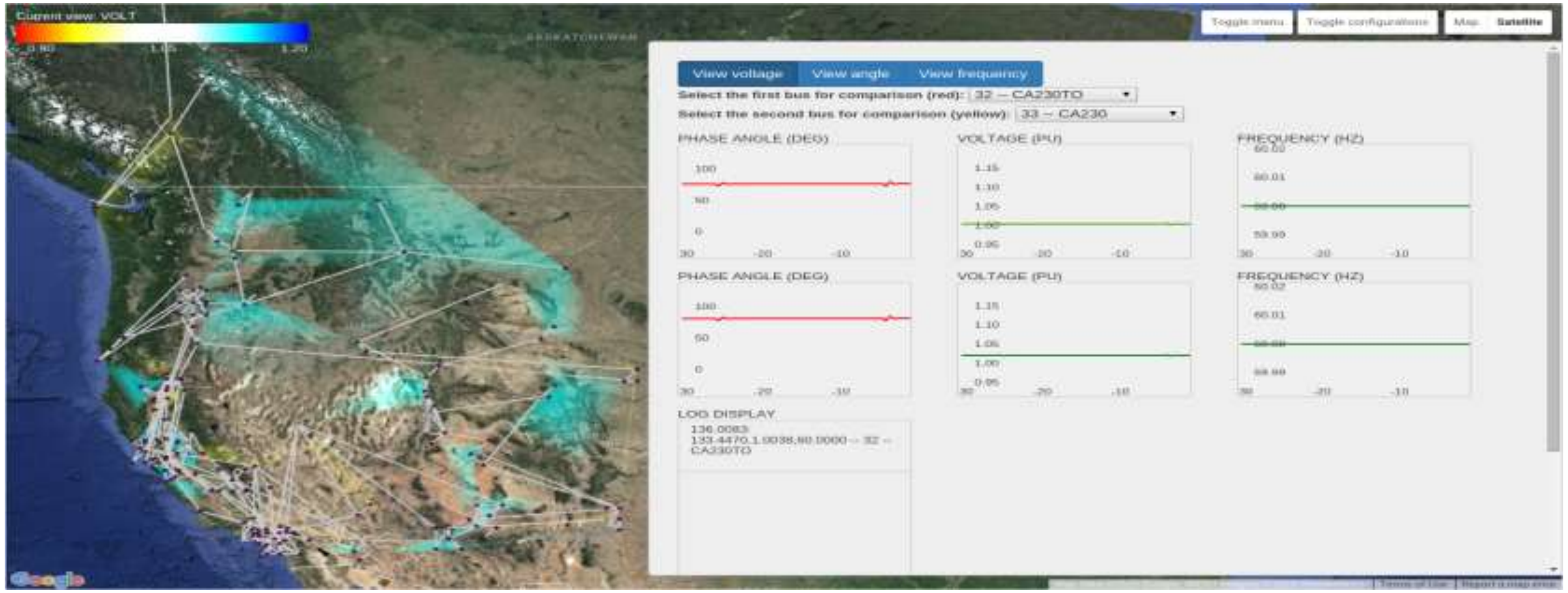
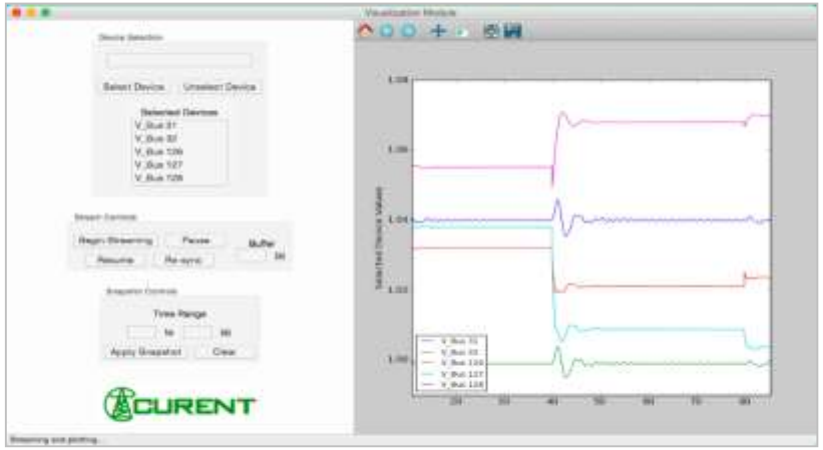
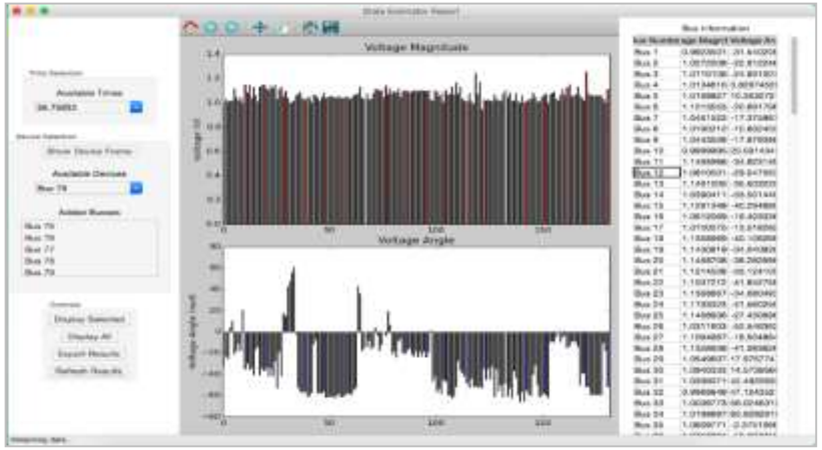
LTB Demonstration with MATLAB Simulator



GIS Visualization

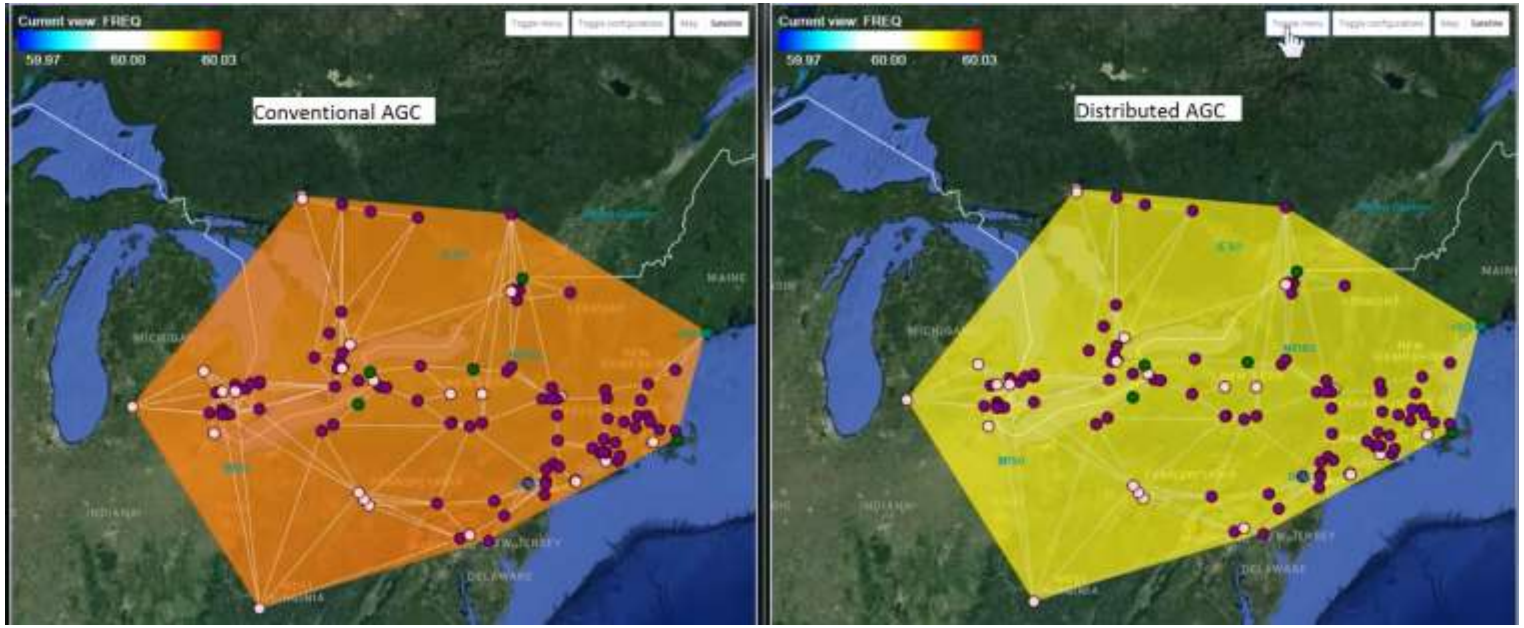


Main Control Panel



State Estimation Results

LTB Demonstration with Real-Time Simulator



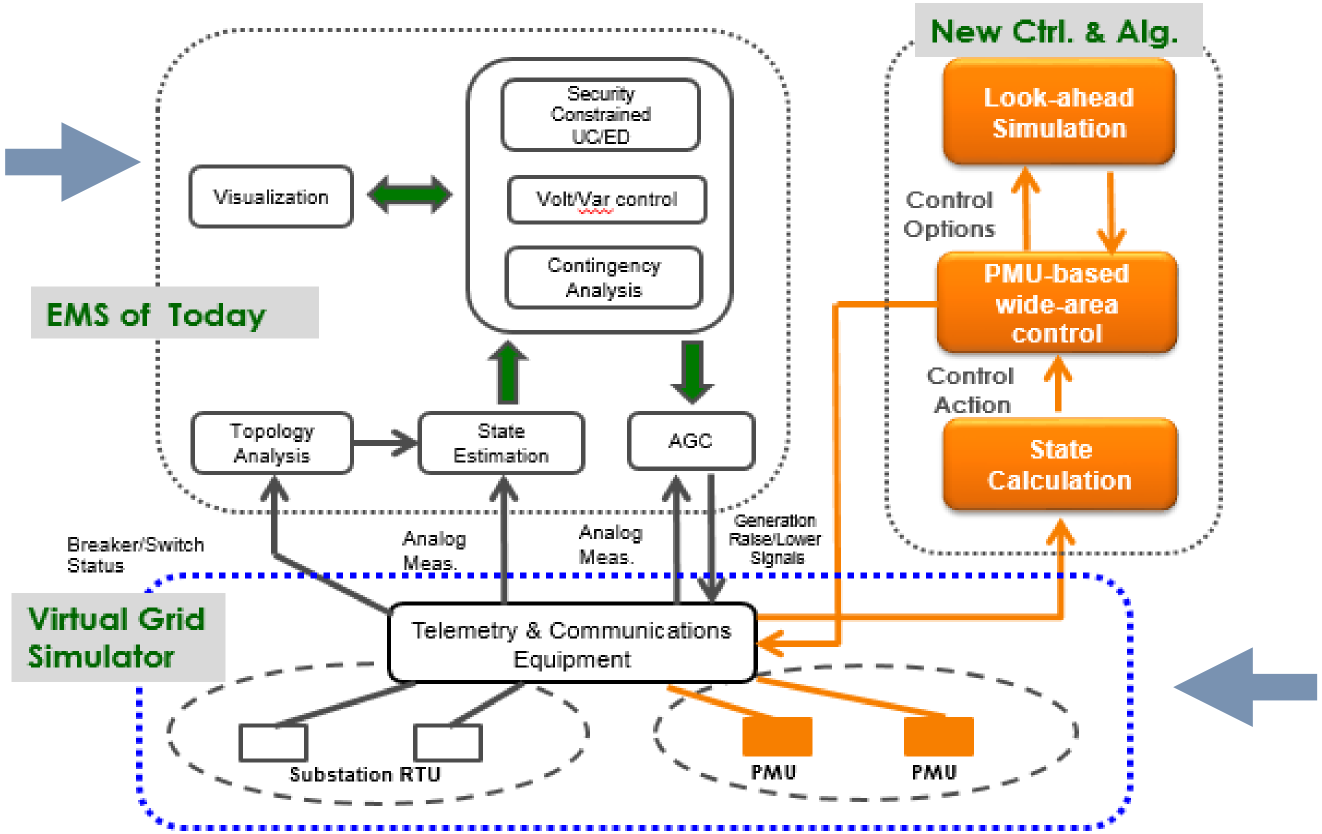
GIS Visualization

OPAL-RT Real-Time Simulator

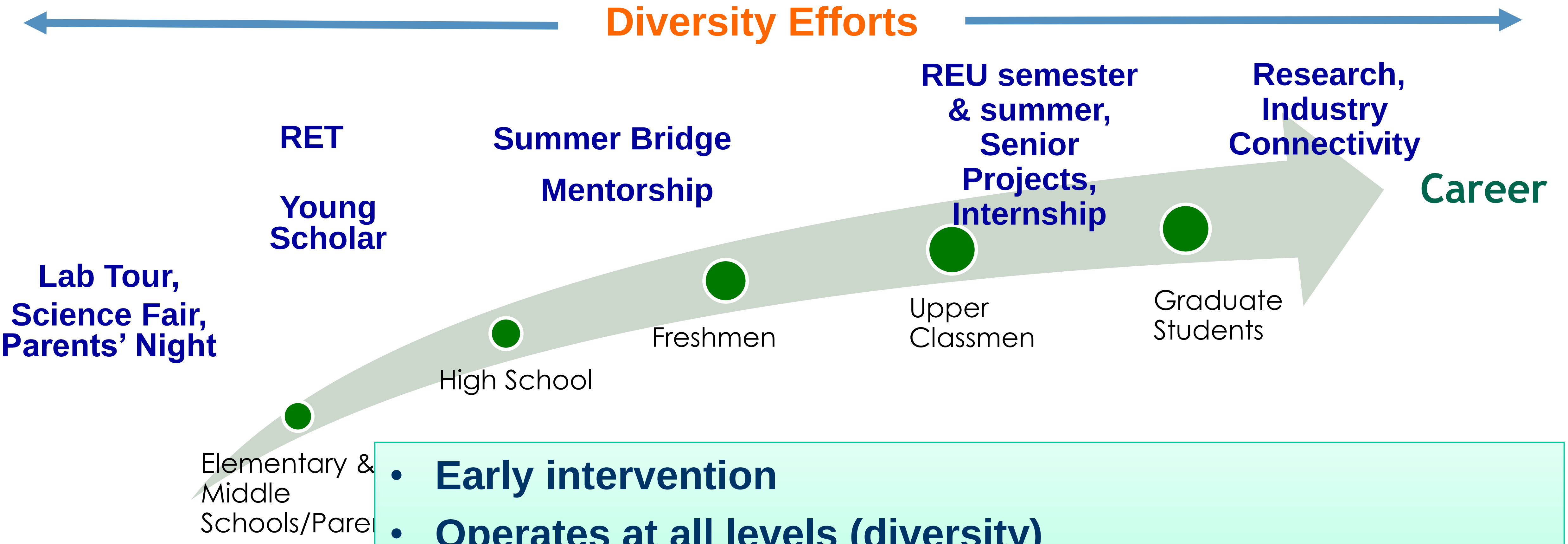
- **Swapped in real-time simulator but use the same visualization module**
- **Interfaced through same communication protocol**
- **Plug n'play functionality with other software**
- **Real-time hardware platform scalable to large systems**

Virtual Grid Simulator with an EMCS

Donations this year by Alstom Grid and Opal-RT will help CURENT showcase wide-area visualization and controls in our large scale testbed in future years.



Education Program Pipeline



- **Early intervention**
- **Operates at all levels (diversity)**
- **Tailored research opportunity**
- **Sustained involvement**
- **Model-based assessment and research**

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Some Possible UWA PMU Based Controls

Slow

- Frequency control
  - Can ACE and area based control be dropped?
  - Local control for frequency and relative "position" (i.e., phase)
  - Simplify integration of new "zero-inertia" generation and controllable load
  - Eliminate division between economic dispatch and frequency control

Fast

- **Supplemental damping control to isolate disturbances**

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Distributed Contextual Control: Frequency Regulation for High Penetration of Wind Generation

Maryam H. Variani, Kevin Tomsovic

Introduction

- Frequency regulation at conventional units need to be modified to cope with high penetration of wind because:
  - A new and potentially large component is added to the requirement for secondary response with respect to both amount and rate of delivery
  - The assumption that frequency error throughout a balancing authority is identical may not be well suited for systems with high wind penetration because larger imbalances may occur at locations with high installed wind capacity
  - And …
- Studies show that it may be both technically and economically feasible for wind plants to supply regulation under some circumstances

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Introduction

- Two-Level Control Structure
  - ➢ To allow high penetration (e.g., 50%) of renewable resources, conventional controls need to be replaced by a simpler structure.
  - ➢ The proposed structure consists of local control operating within a global context of situational awareness at different levels.

Flatness-based approach is well adopted to control systems in two levels of planning, trajectory generation, and tracking the desired trajectories.

C	
se sy be ov moment	o y o manage deviations

Flatness Based AGC

- Flatness-based approach is applied to automatic generation control(AGC) of multi-area systems with wind generation units.

- In two level control structure, secondary control action represents local control and the contextual control determines the reference trajectory to be tracked by the local control.

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Flatness Based AGC

AGC equations in original space for generator *i*

$$\dot{\delta}_i = \omega_i - \omega_s$$

$$\dot{\omega}_i = \frac{1}{2H}\left[P_{mi} - D(\omega_i - \omega_s) - \frac{E_i V_i}{x'_{di}} sin(\delta_i - \theta_i)\right]$$

$$\dot{P}_{gvi} = \frac{1}{\tau_{gi}}\left(P_i^{ref} - \frac{\omega_i - \omega_s}{R\omega_s} - P_{gvi}\right)$$

$$\dot{P}_{mi} = \frac{1}{\tau_{Ti}}\left(P_{gvi} - P_{mi}\right)$$

Deriving AGC equations in flat space

$$\begin{cases} \delta_1^{(4)} = v_1 \\ \vdots \\ \delta_n^{(4)} = v_n \end{cases} \Rightarrow$$

$$\dot{\delta}_i = \omega_i - \omega_s$$

$$\ddot{\delta}_i = \frac{1}{2H}\left[P_{mi} - D(\omega_i - \omega_s) - \frac{E_i V_i}{x'_{di}} sin(\delta_i - \theta_i)\right]$$

$$\dddot{\delta} = \frac{1}{2H}\left[\frac{1}{\tau_T} P_{gvi} - \frac{1}{\tau_T} P_{mi} - D\ddot{\delta}_i - \frac{E_i V_i}{x'_{di}} \dot{\delta}_i \sin(\delta_i - \theta_i)\right]$$

$$\delta^{(4)} = \frac{1}{2H}\left[\frac{1}{\tau_T \tau_g} P_i^{ref} + \cdots\right]$$

Flatness-based AGC: Trajectory Generation

- In contextual level the desired operating points can be determined through system measurements. In this work economic dispatch is performed.
- To follow load changes and wind variations the operating point is updated every 5 minutes.
- Trajectory generation

$$\delta^*(t) := \sum_{i=0}^{9} a_i \left(\frac{t}{T}\right)^i \quad , T = 5 * 60\ sec$$

- The trajectory is calculated for each generator independently.

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Flatness-based AGC: Trajectory Tracking

- System perturbations: load changes, generation loss, wind generation variations.
- Finding appropriate speed changer position to maintain system stability, restore the frequency nominal value and track the scheduled net interchange.
- Using linear control methods for each generator independently:

$$\delta_i^{(4)} = v_i$$

$$P_i^{ref} = a(\delta_i, \dot{\delta}_i, \dots, \delta_i^{(4)})$$

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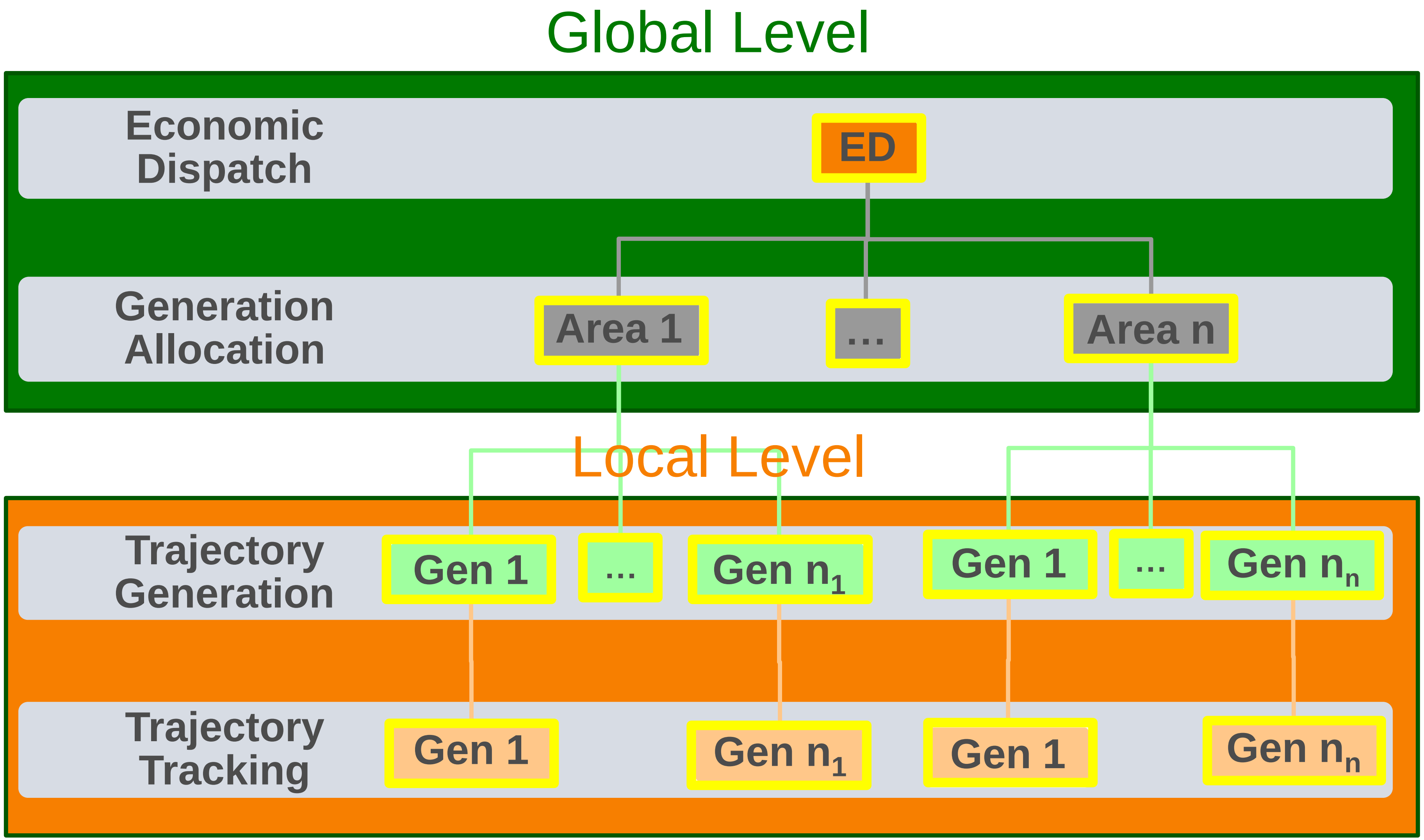
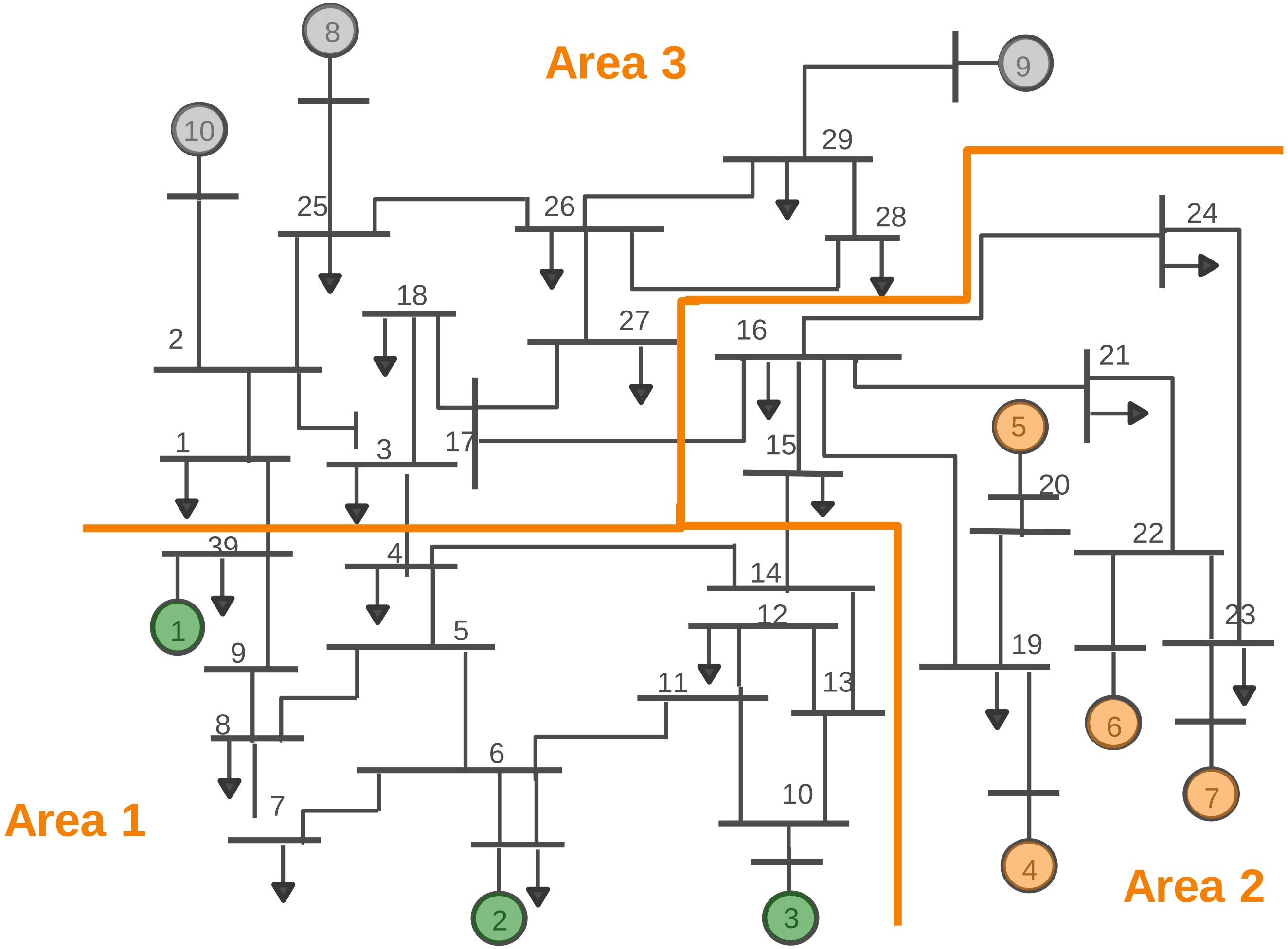
Two Level Flatness-based AGC Structure



Simulation: Case Study

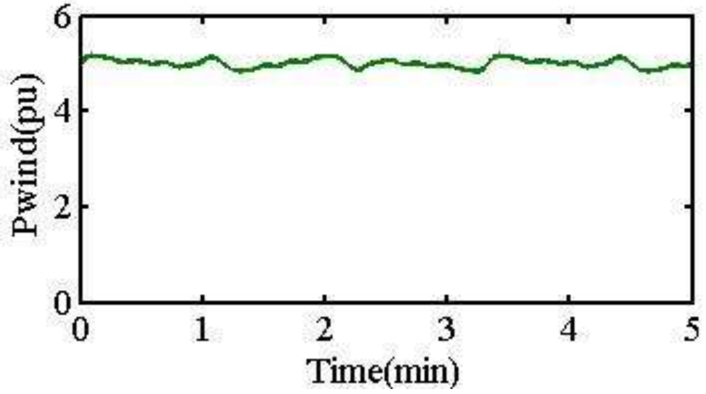
New England 39 Bus, 10 Generators System

Total Load ≈ 5.5 GW



Simulation: Scenarios

- Wind power generation added to the system:



- Active power schedule values with ED:

		Area 1			Area 2				Area 3		
Scenarios	% wind	1	2	3	4	5	6	7	8	9	10
No wind	0	5.62	3.73	3.73	7.48	7.80	5.80	4.30	4.30	4.30	7.80
Wind in Area 2	10%	5.62	3.73	3.73	7.48	7.80	5.09	0	4.30	4.30	7.80
Wind in Area 1&2	20%	5.62	2.45	0	7.48	7.80	5.09	0	4.30	4.30	7.80

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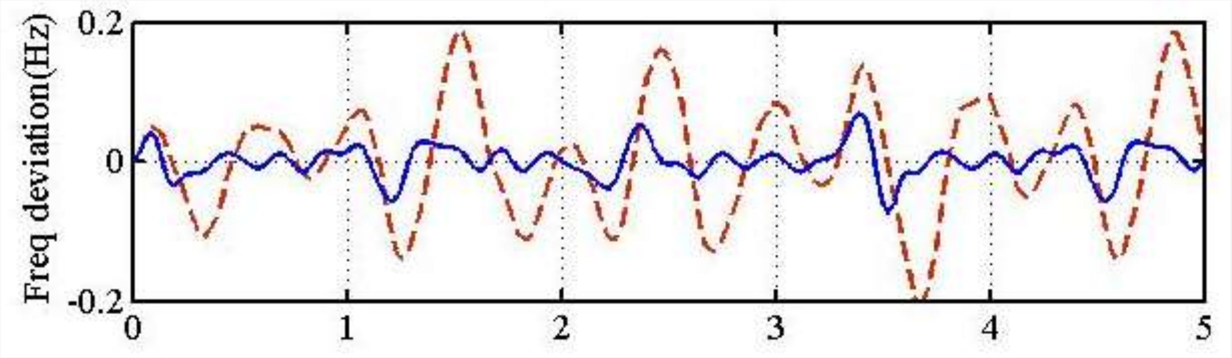
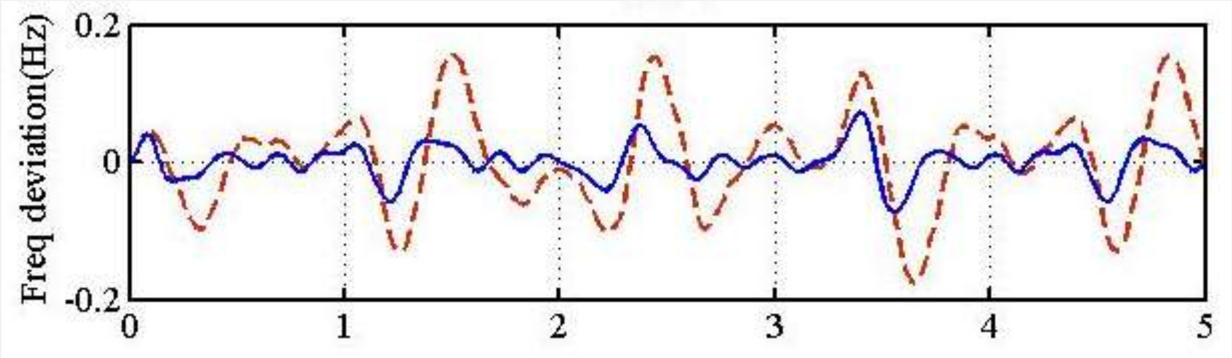
Simulation: Results, 20% Wind

- Frequency deviations with wind generation in areas 1& 2. (Flat: Blue, Conventional : red)
  - ➢ Reduced deviations compared to conventional.

Area 1	
Area 2	

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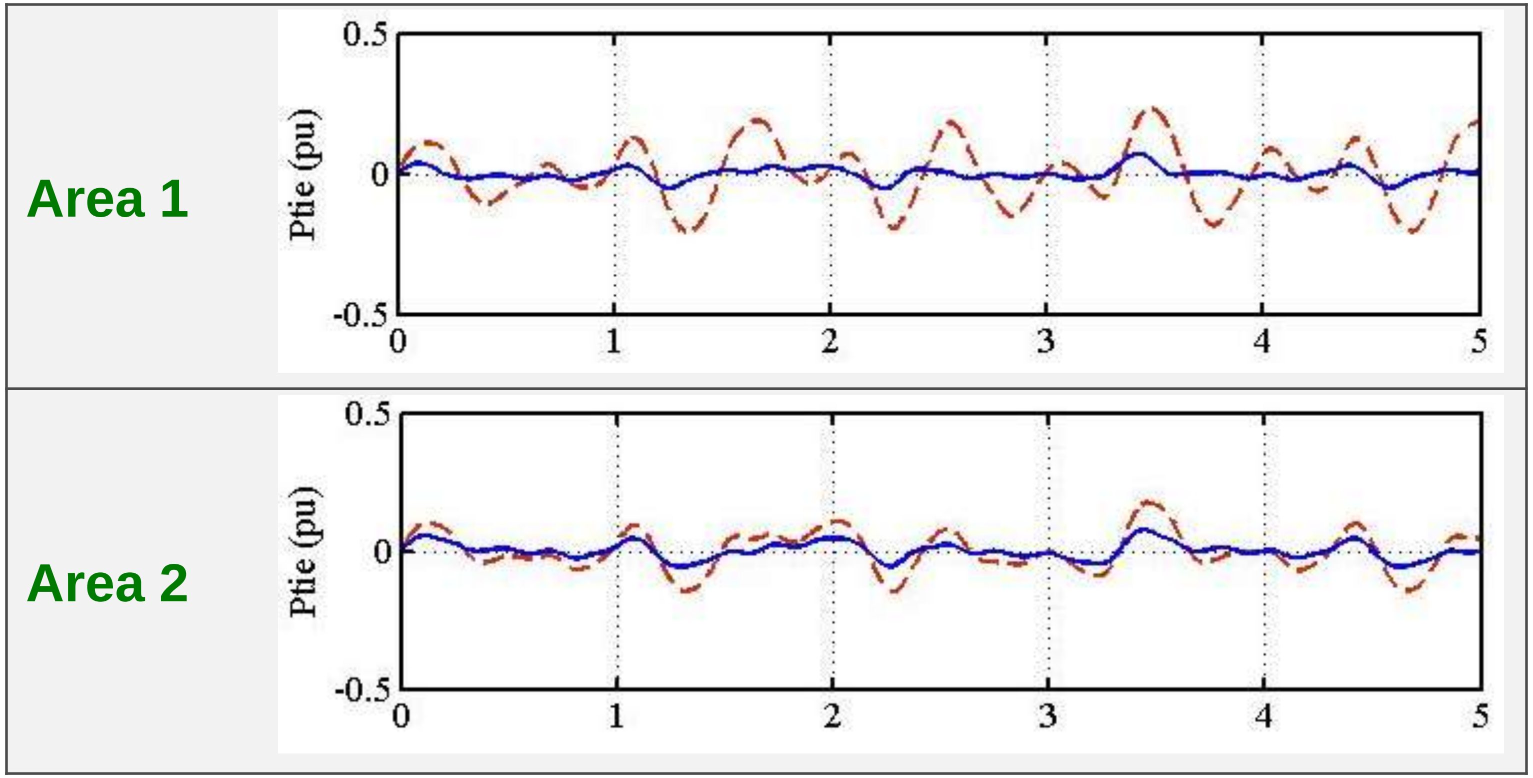
Simulation: Results, 20% Wind

- Tie line power flow deviations with wind generation in areas 1&2. (Flat: Blue, Conventional : red)
  - Reduced deviations compared to conventional.



Flatness-based DFIG

- Trajectory generation:
  - The reference values for active and reactive powers in a wind farm are sent by supervisory control.
  - Trajectories for system states are generated at wind turbine level control.
  - The generated active and reactive power of DFIG are:

$$P_g = \left(V_{ds} i_{ds} + V_{qs} i_{qs}\right) - \left(V_{dr} i_{dr} + V_{qr} i_{qr}\right)$$
$$Q_g = \left(V_{qs} i_{ds} - V_{ds} i_{qs}\right)$$

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Flatness-based DFIG

- It suffices to find k_i coefficients with linear methods such as pole placement, LQR and … .

Using flatness-based approach PI Controller to track the reference values, in field oriented control, are replaced with finding k_i coefficients through simple linear methods

Simulation Results

- The simulation is performed in a system with a DFIG connected to an infinite bus.
- Mechanical torque is assumed to be constant.
- Two scenarios are studied:
  - Scenario 1: Step change in reference active power
  - Scenario 2: Step change in reference reactive power

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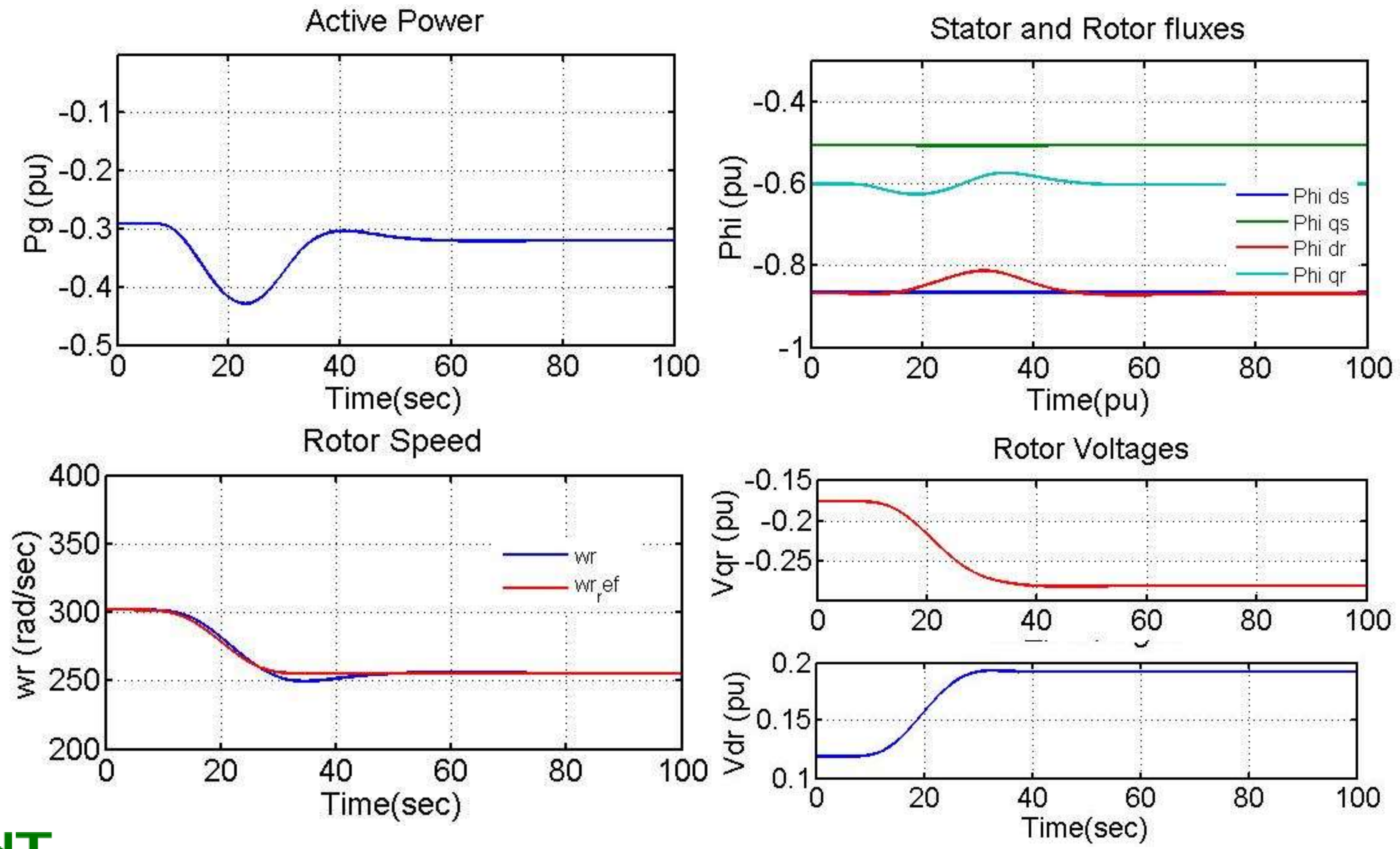
Simulation Results: Scenario 1



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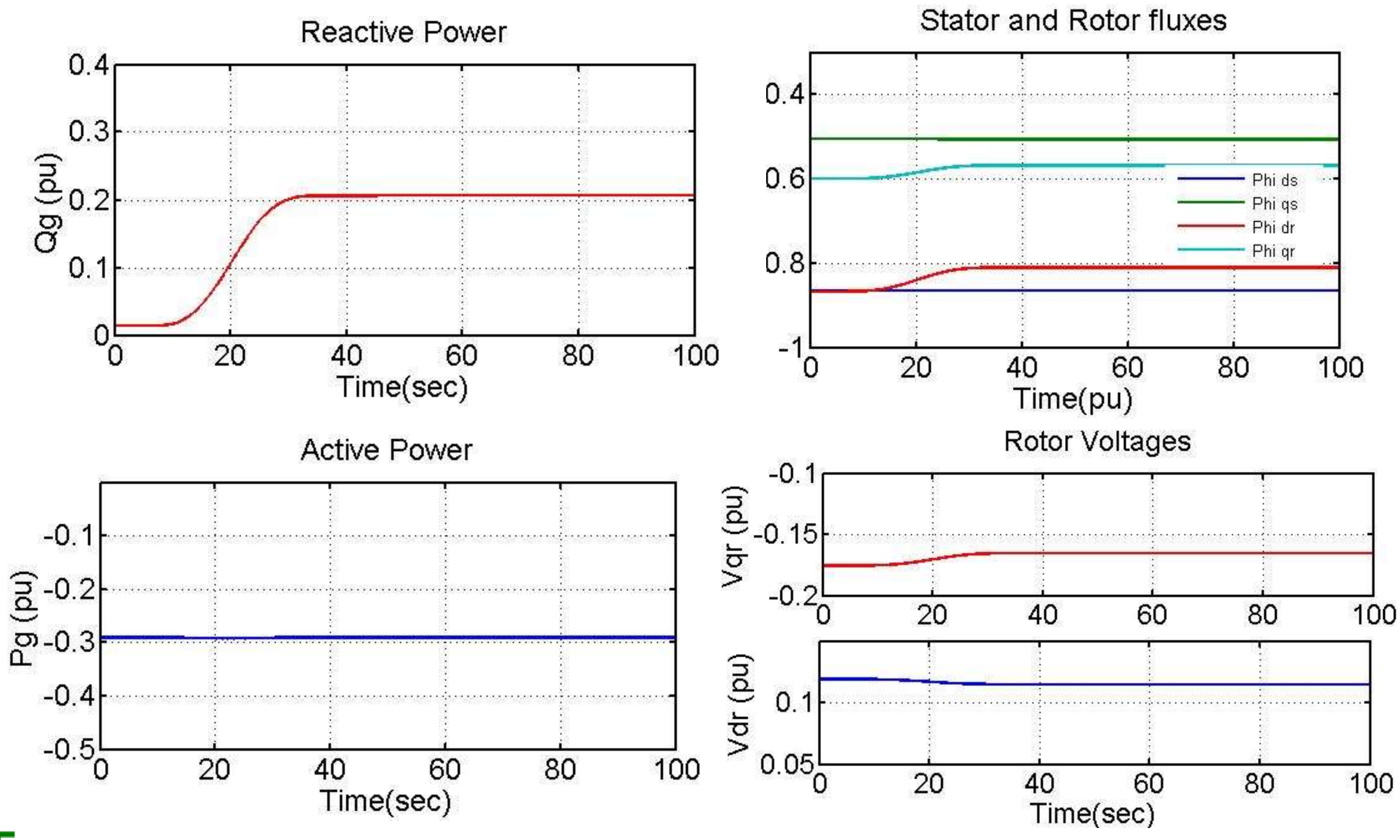
Simulation Results: Scenario 1

- A step change in the reference value for active power
  - ω_r is gradually reduced to follow the changes in the active power and resulted in the balance between electrical and mechanical torques in steady state.
  - The stator fluxes remained constant in simulation time. φ_{qr} followed the reference trajectory and φ_{dr} has changed accordingly.
  - The designed controls, V_{dr} and V_{qr} are shown in figures.

Simulation Results: Scenario 2



Simulation Results: Scenario 1

- A step change in the reference value for reactive power
  - The active power remained constant during simulation.
  - No changes is observed in stator flux. φ_{qr} followed the reference trajectories and φ_{dr} has also changed to result in the desired reactive power.
  - The designed controls, V_{dr} and V_{qr} are shown in figures.

Comments

- Two level control based on flatness properties is studied for synchronous and DFIG machines for frequency regulation and voltage control.
- Control architecture
  - Similar to today's AGC and Economic dispatch – control center based BUT
    - Many more devices contributing
    - Faster coordination
    - Integrate overall system objectives – security, economics, voltage and frequency requirements

Comments

- Flatness-based DFIG control
  - ➢ Two level control consisting of trajectory generation and trajectory tracking replaces the field oriented based method to control active and reactive power.
  - ➢ Trajectories are generated through algebraic equations rather than PI controllers.
  - ➢ Linear control methods such as pole placement and LQR replace the PI controller to track the desired states.
  - ➢ This structure, along with flatness-based AGC, will build a generic model with two level controls at each machine working in coordination with higher level controls for planning.

Distributed Control to Mitigate Disturbances in Large Power Networks

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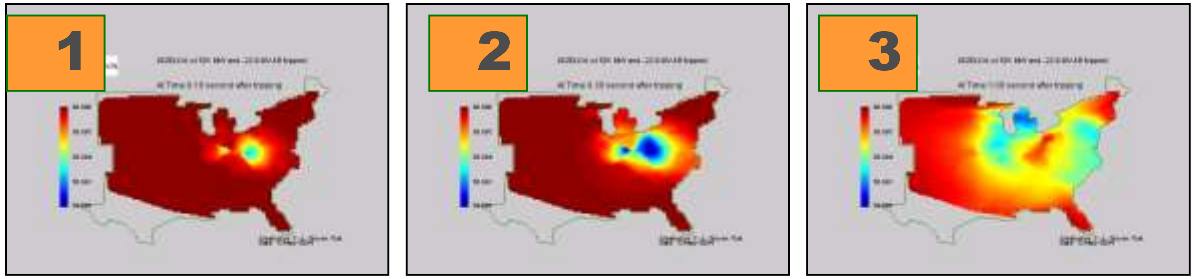
Tasks in this Work

- Investigating the possibility of less disruptive supplementary inputs to existing controls rather than the more severe switching operations, such as, generation rejection, control blocking or other discrete operations, in today's RAS.
- Understanding the performance trade-offs among distributed and more centralized control architectures.
- Developing a framework to model the interaction among control schemes and understanding of the reliability implications.

A Key Challenge in Power Network Analysis

- A key challenge is **<u>how to model the propagation of perturbations</u>**, which determines the power network stability and helps to design the control mechanism.



- Our research is partly motivated by **<u>Continuum Modeling</u>** of Electromechanical Dynamics in Large-Scale Power Systems which suggests that disturbances in power systems will propagate as **<u>traveling waves</u>**.

Wide Area Control of Power Grid

- The addition of **wide-area feedback control** to frequently used controls is an effective additional layer of defense against blackouts.
- **<u>Centralized Control :</u>** a single controller is able to measure all the system outputs, compute the optimal control solution, and apply that action to all actuators in the network, within one sampling period.

As power networks are large-scale systems, both computationally and geographically, a Centralized Wide Area Controller is practically difficult to implement.

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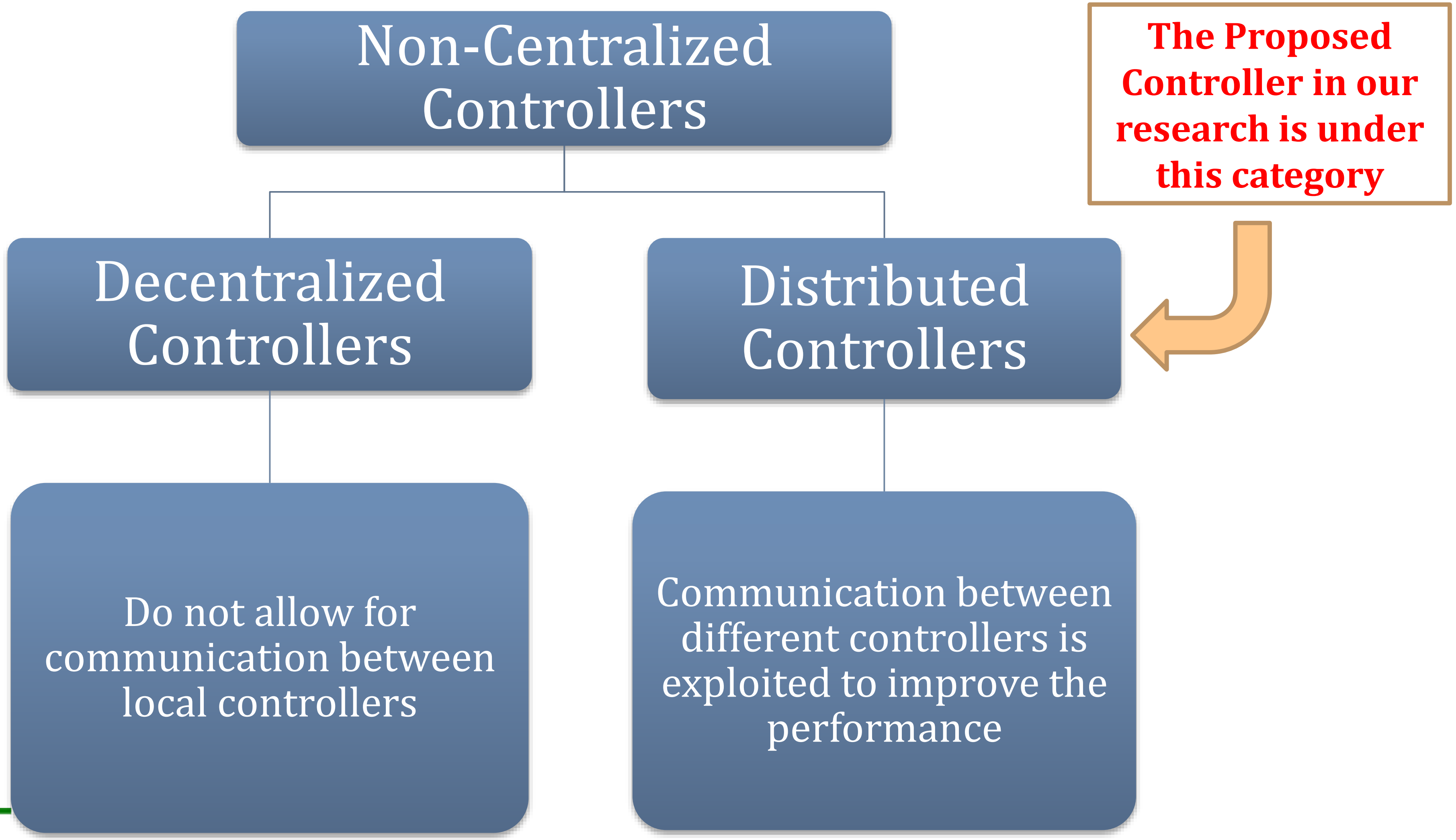
Non-Centralized Controllers



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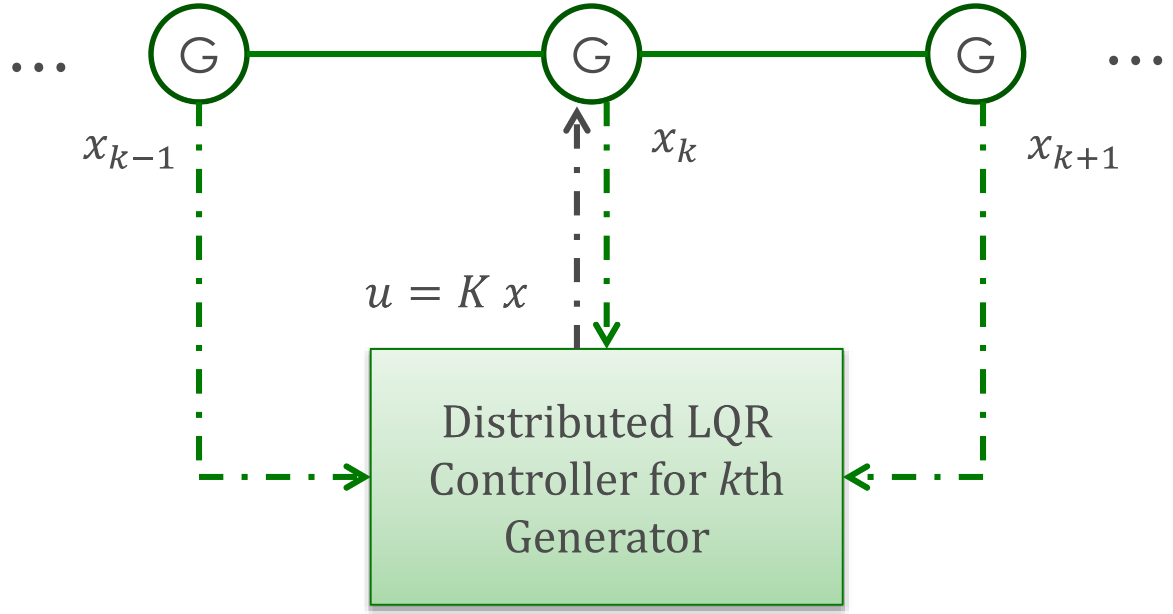
Proposed Distributed LQR Controller

- <u>Objective</u>: Stabilize the system through supplementary excitation control
- Graph of physical layer and communication layer coincide.
- **Full state information** exchange is assumed for **neighboring** generators



Distributed LQR Controller

- Consider a set of N_L identical, decoupled linear time invariant dynamical systems:

$$\dot{x}_i = Ax_i + Bu_i$$
$$x_i(0) = x_{i0}.$$

- LQR Problem Cost Function:

$$J(\tilde{u}, \tilde{x}_0) = \int_0^\infty \left(\sum_{i=1}^{N_L} (x_i(\tau)' Q_{ii} x_i(\tau) + u_i(\tau)' R_{ii} u_i(\tau)) + \sum_{i=1}^{N_L} \sum_{j \neq i}^{N_L} (x_i(\tau) - x_j(\tau))' Q_{ij} (x_i(\tau) - x_j(\tau)) \right) d\tau$$

- The LQR problem is in the form of :

$$\min_{\tilde{u}} \quad J(\tilde{u}, \tilde{x}_0) \qquad \text{subj. to } \dot{\tilde{x}} = \tilde{A}\tilde{x} + \tilde{B}\tilde{u} \qquad \tilde{x}(0) = \tilde{x}_0$$

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Power System Model

Distributed LQR Control	
Mechanical Power Control	Excitation Control
Second-Order Model	Fourth-Order Model

Mechanical Power Control — Second-Order Model

$$\frac{d}{dt}\omega(t) = \frac{\pi f_s}{H}(P_m - P_e - P_D + P_{DLQR})$$

$$\frac{d}{dt}\delta(t) = \omega(t) - \omega_s(t)$$

Excitation Control — Fourth-Order Model

$$\frac{d}{dt}\omega(t) = \frac{\pi f_s}{H}(P_m - P_e - P_D)$$

$$\frac{d}{dt}\delta(t) = \omega(t) - \omega_s(t)$$

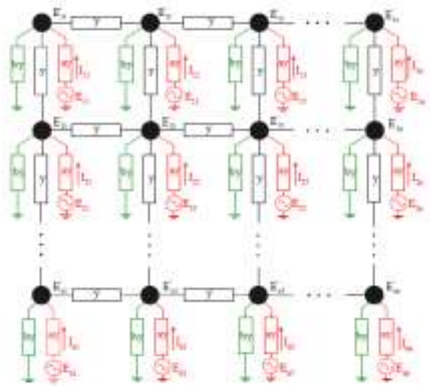
$$\frac{d}{dt}E_q'(t) = \frac{1}{T_{d0}'}[E_{fd}(t) - E_q'(t) - (X_d - X_d')I_d(t)]$$

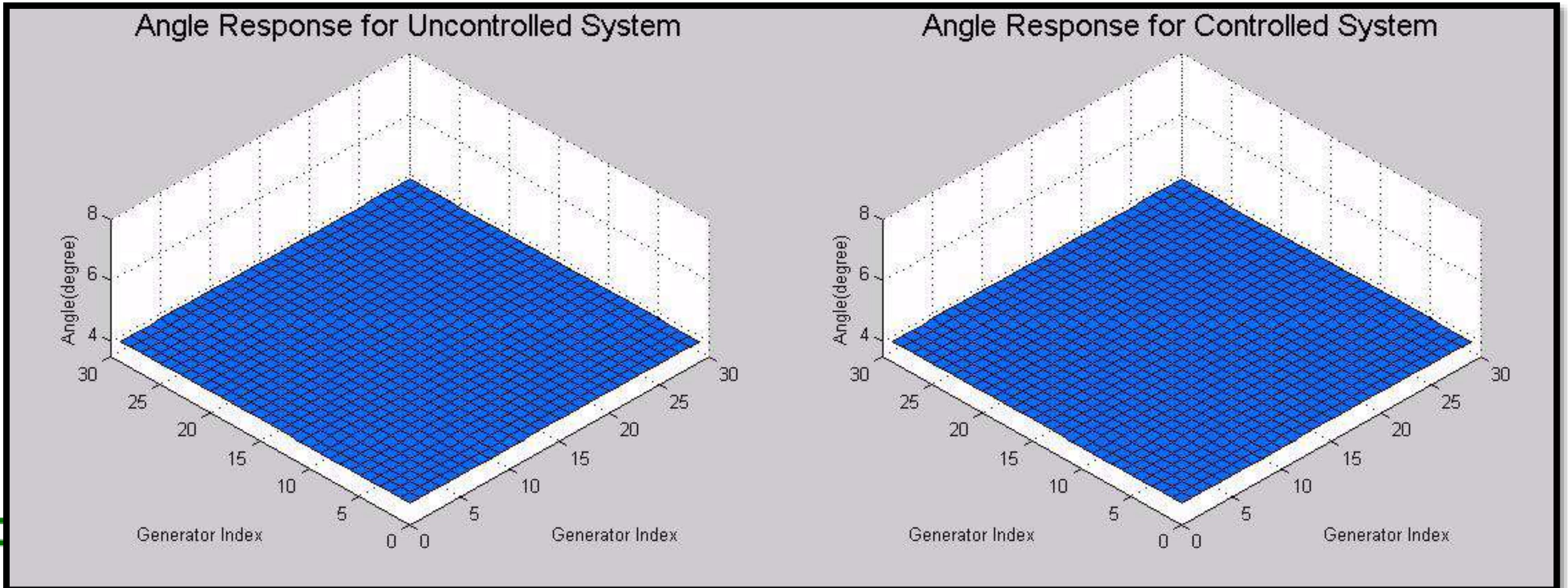
$$\frac{d}{dt}E_{fd}(t) = \frac{1}{T_A}[-E_{fd} + K_A(V_{ref} - E_t + V_{DLQR}(t))]$$

Designed by Proposed Distributed LQR Controller

Angle Response for Uniform Test System

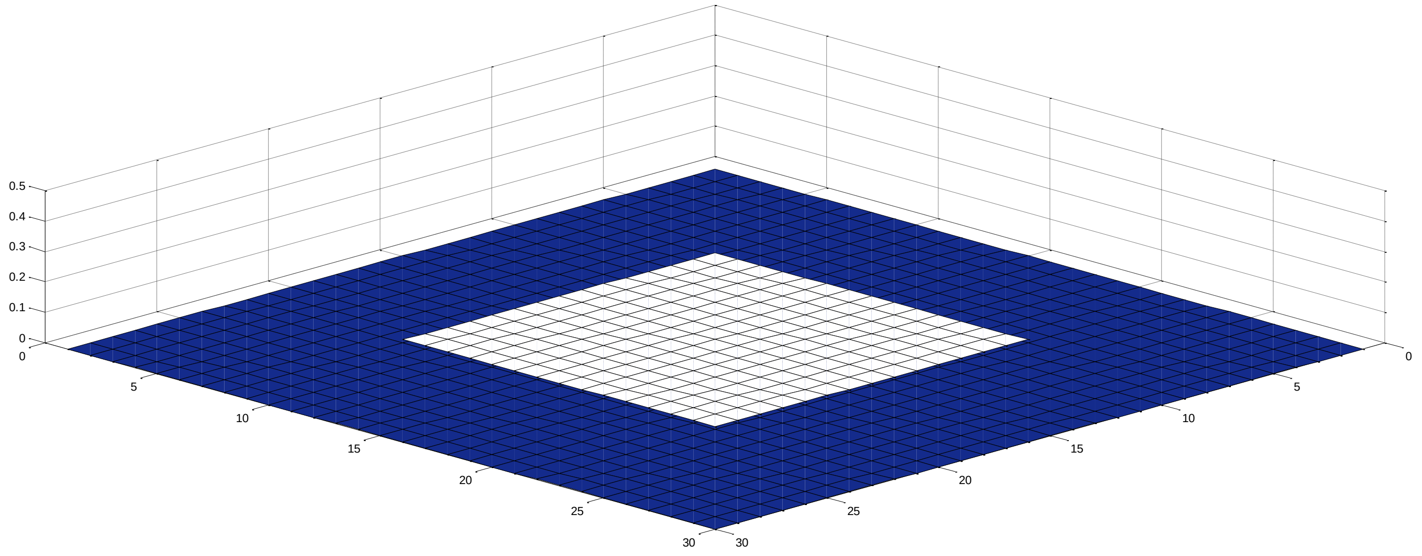
- **System** : 30x30 Mesh structure(Total of 900 generators)
- **Disturbance** : 0.5 pu power pulse for 0.5 sec on the generator in the center of the mesh



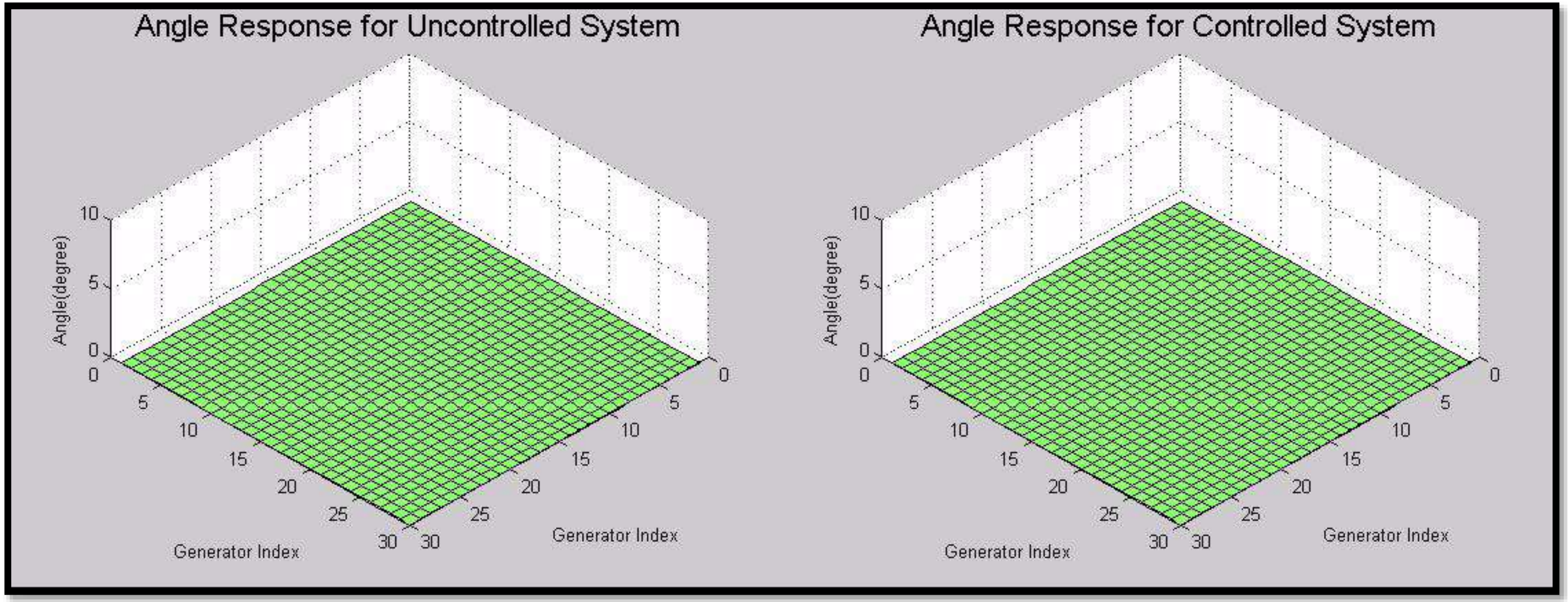


Non-uniform System Structure

- All the transmission lines in the white area have been removed from the system.
- All other transmission lines have the same impedance of :
- $Z_{transmission} = (3.2 \times 10^{-4}) jpu\ per\ mile$

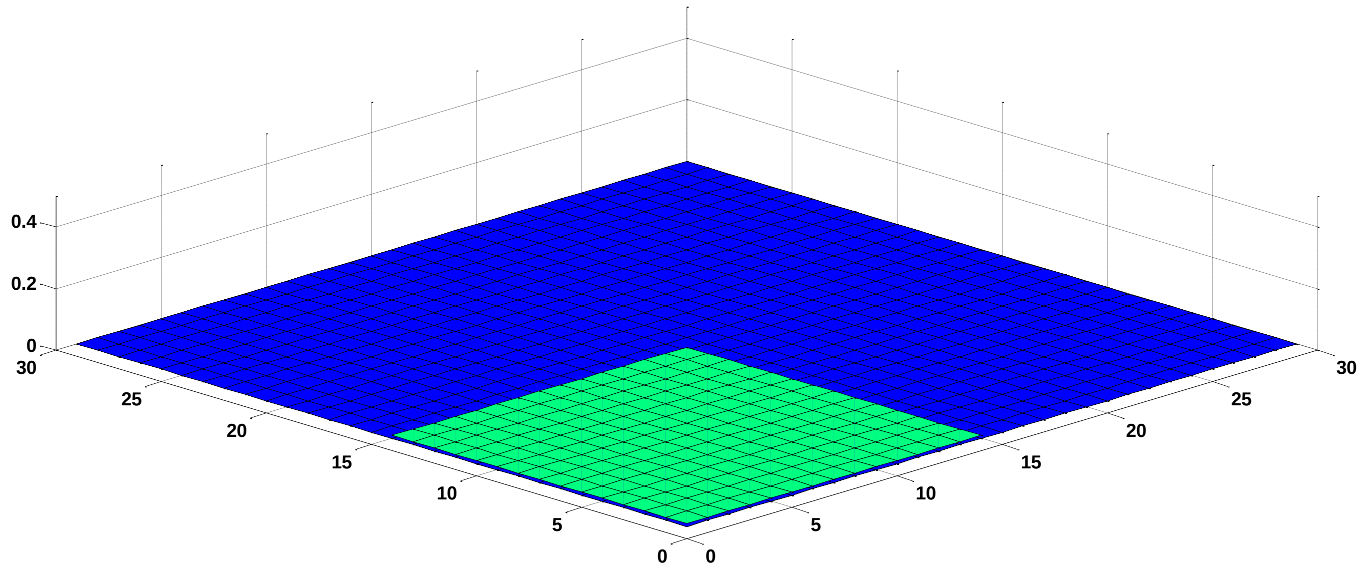


Angle Response for Non-uniform Test System

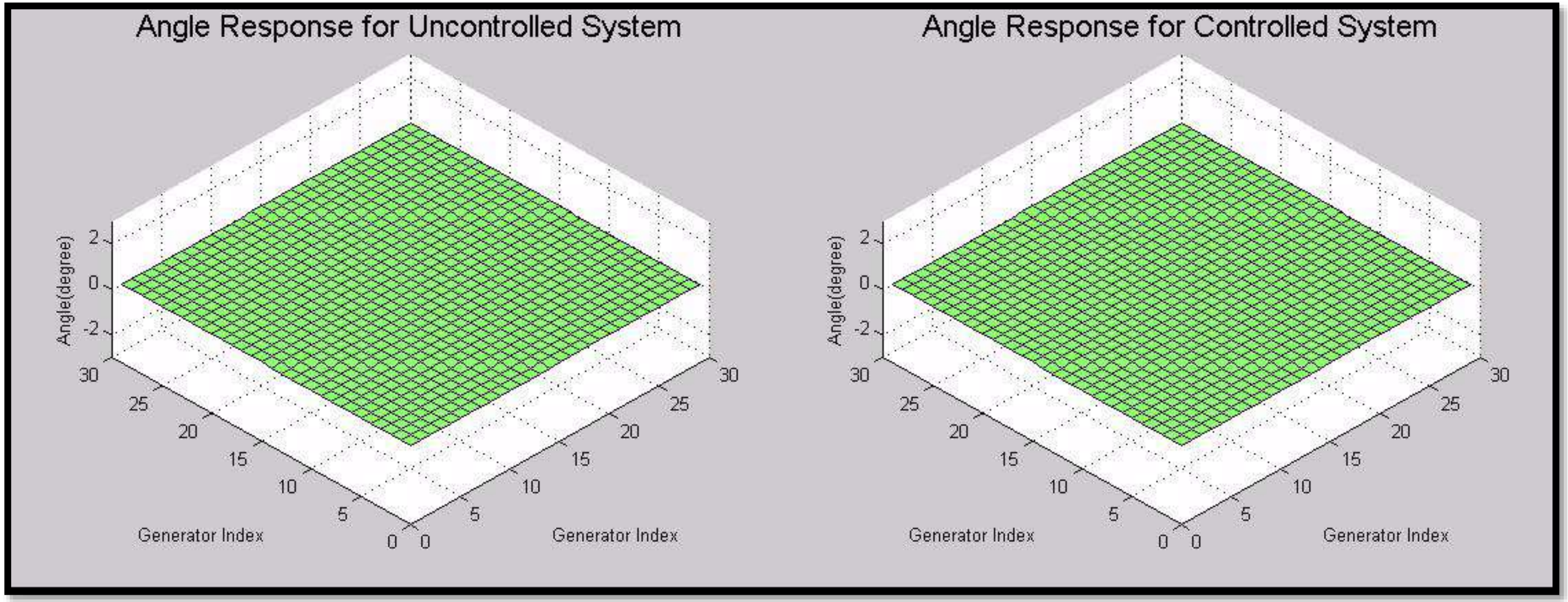


Non-uniform Transmission Line Reactances

- All the transmission line reactances in green area have been **increased by factor of 2**.
- Initial Reactances: $Z_{transmission} = (3.2 \times 10^{-4}) j pu\ per\ mile$



Angle Response for Test System with Non-uniform Line Reactances



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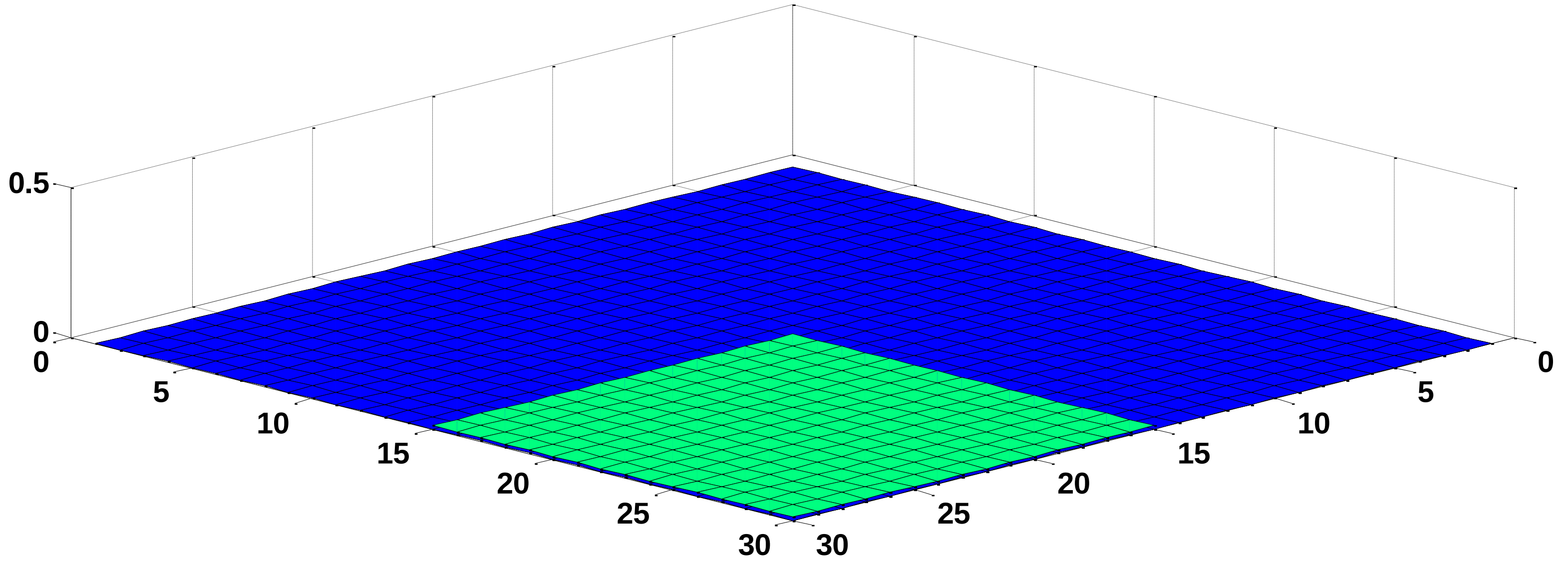
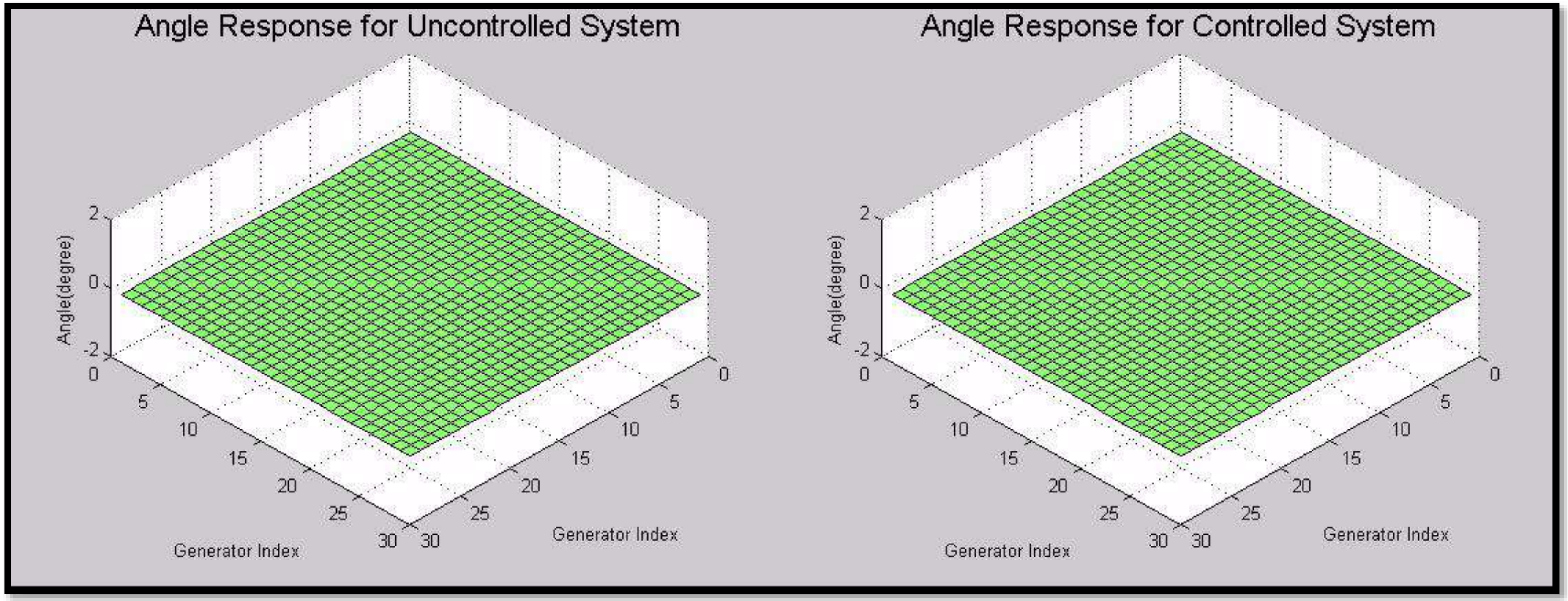
Non-uniform Machine Inertias

- All generator inertias in the green area are 3s compared to blue area with inertia of 6s.



Angle Response for Test System with Non-uniform Machine Inertias



Remarks

- From control point of view distributed LQR control problem for PDEs achieves optimal solution, while for discrete models the solutions are sub-optimal and still is an open problem.
- For the given test system we can do the discretization in a way that matches the generators location which makes the controller application to the discrete system feasible. Application of this controller to an arbitrary system is a challenging problem that will be part of our future work.

Discussion

Reading list

1. C.W. Taylor, et al., "WACS – Wide-area stability and voltage control system: R&D and Online Demonstration," *Proceedings of the IEEE*, Vol. 93, No. 5, May 2005.
2. V. Terzija, et al., "Wide-Area monitoring, protection and control of future electric power networks," *Proceedings of the IEEE*, Vol. 99, No. 1, Jan. 2011.
3. K. Tomsovic, et al., "Designing the Next Generation of Real-Time Control, Communication and Computations for Large Power Systems," *Proceedings of the IEEE,* Vol. 93, No. 5, May 2005.

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.

Test Question

1. In reference to the California-Oregon Intertie.
   - What was the expected capacity for the original design?
   - What was the reason for the lower limit?
   - What was the actual transfer limited to initially?
   - What controllers were added to increase the transfer limit?
2. Identify wide area controls that exist in the power system today. You should name at least one common to most systems and then one or two others that are less common. Give a short description of the functionality of any control you identify (you won't find all this in the slides).