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Enabling Control Systems in Power Grids with High Renewable Penetration

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

Center for Ultra-Wide-Area Resilient Electric Energy Transmission Networks

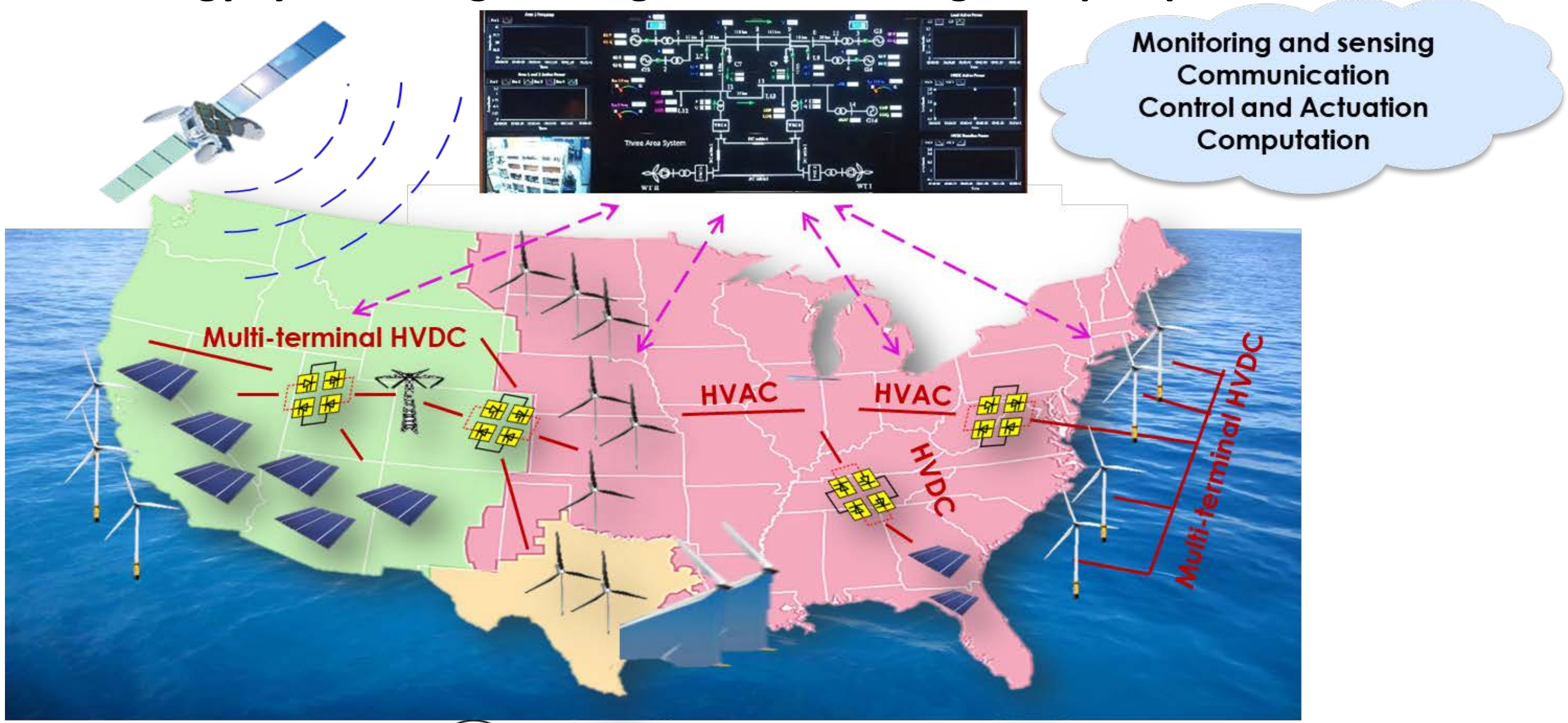
Center Director: Professor Kevin Tomsovic, University of Tennessee, Knoxville

Missions:

- **Nation-wide transmission grid, fully monitored and dynamically controlled, for high efficiency and reliability, low cost, integration of renewable sources, full utilization of storage, and responsive load**
- **Develop new generation of electric power and energy systems engineering leaders with a global perspective coming from diverse backgrounds**

Motivations:

- **Energy sustainability is one of the most fundamental societal needs**
- **Reliance on fossil fuels creates significant environmental and national security issues**
- **Changing and uncertain generation mix due to renewables**
- **Solution requires a new approach to power transmission and distribution and control solutions**



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Introduction:
System Operation with High Renewable Penetration

- Renewable penetration in several countries most likely >50% after 2030; many older fossil and nuclear units will be retired
- The 2030 systems will have:
  - About the same AC transmission system
  - Up to 80% fewer large synchronous machines, with longer distance between neighboring units
  - Grid scale integration of wind and solar, at subtransmission voltage levels
  - Distributed solar generation at distribution voltage level (less dispatchable/controllable)
- System has less total rotating inertia (hydraulic units are still operating)
  - AC generating units support main transmission grid – renewables in grid-following mode vs grid-forming mode
  - Frequency response may deteriorate
- Converters located between AC generating units to provide voltage support
- Renewable resources will dominate on low-load, high-renewable days: renewable resources may be curtailed and used for backup and regulation
- *To maintain system performance, need to enable renewable resource control – frequency, damping, voltage, and transient stability*

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Hierarchical Frequency Control in Power Systems

Frequency control hierarchy	Conventional AC systems	High renewable systems
Primary frequency control	Governing by steam and hydraulic turbines	Type-3 wind turbines with governing function
Secondary frequency control	Area control error (ACE) and automatic generation control (AGC)	Cross-regional AGC
Tertiary frequency control	optimal redispatch	Renewable forecast

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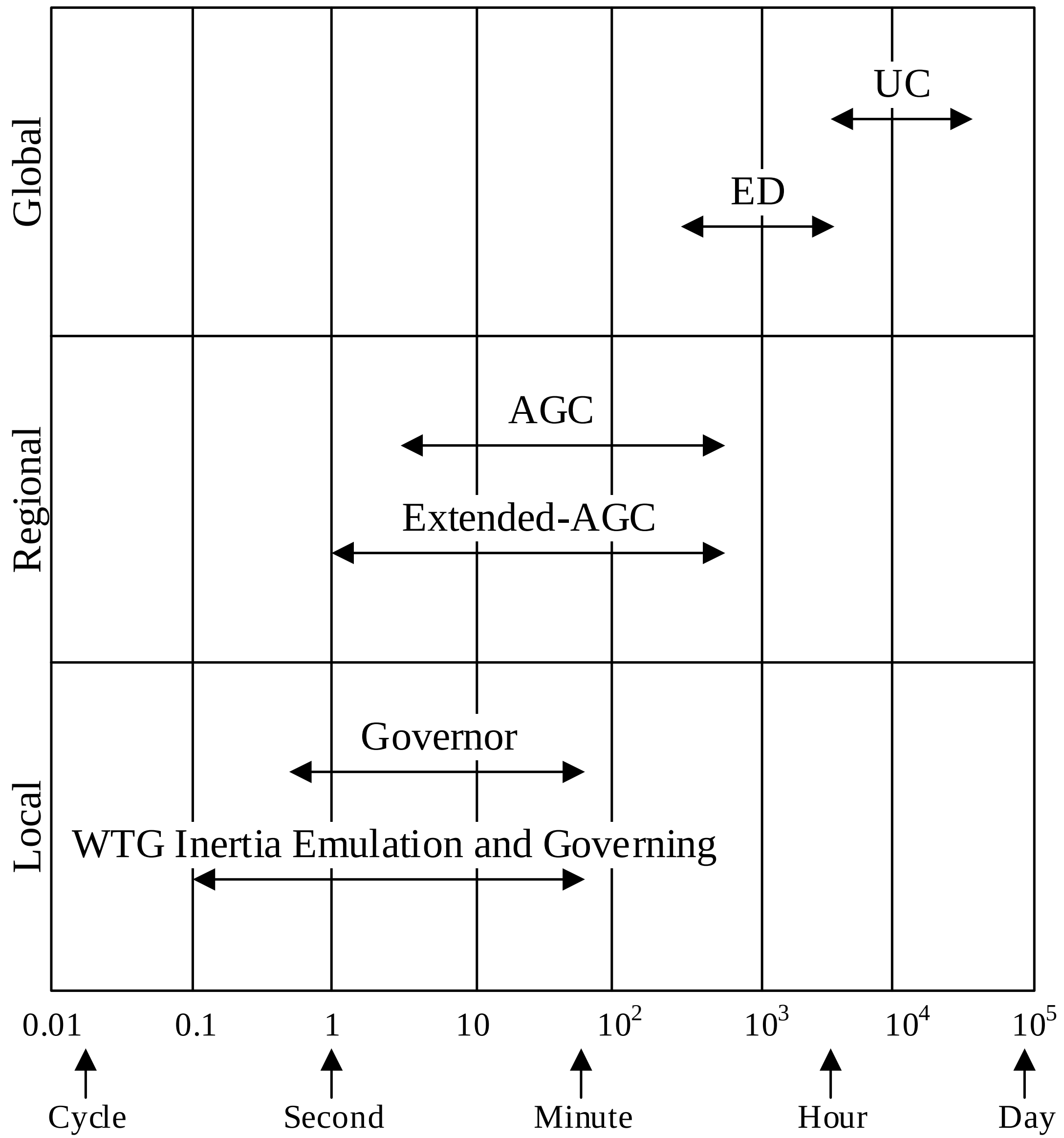
Time Scale of Hierarchical Frequency Control



UC – Unit Commitment

ED – Economic Dispatch

AGC – Automatic Generation Control

WTG – Wind Turbine Generator

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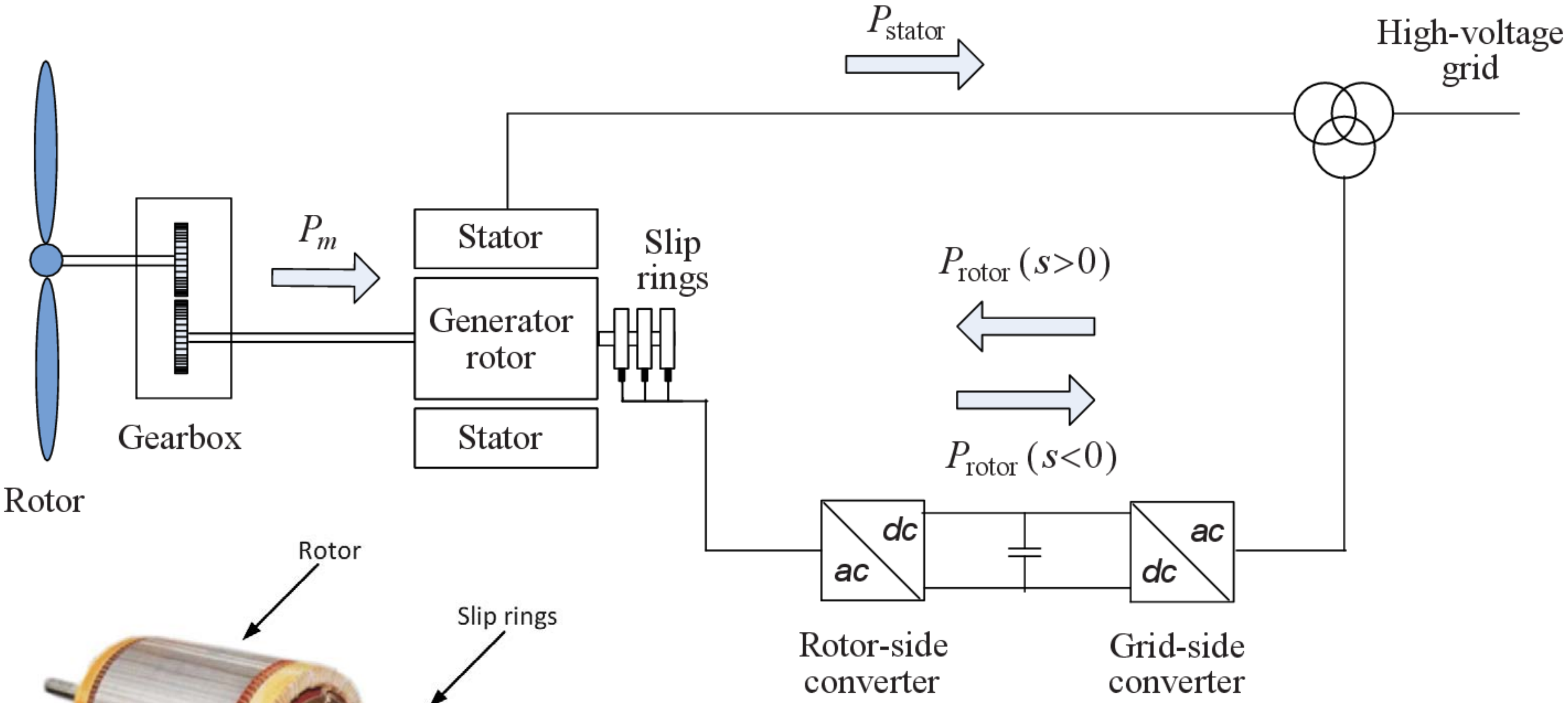
Type-3 WTG Model

- **Converters supply a voltage to the rotor winding of the induction generator**
- **Up to 30% active power circulates between the converters**



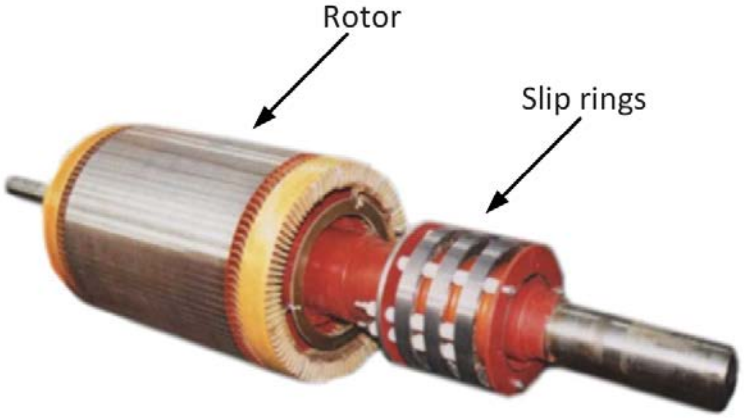


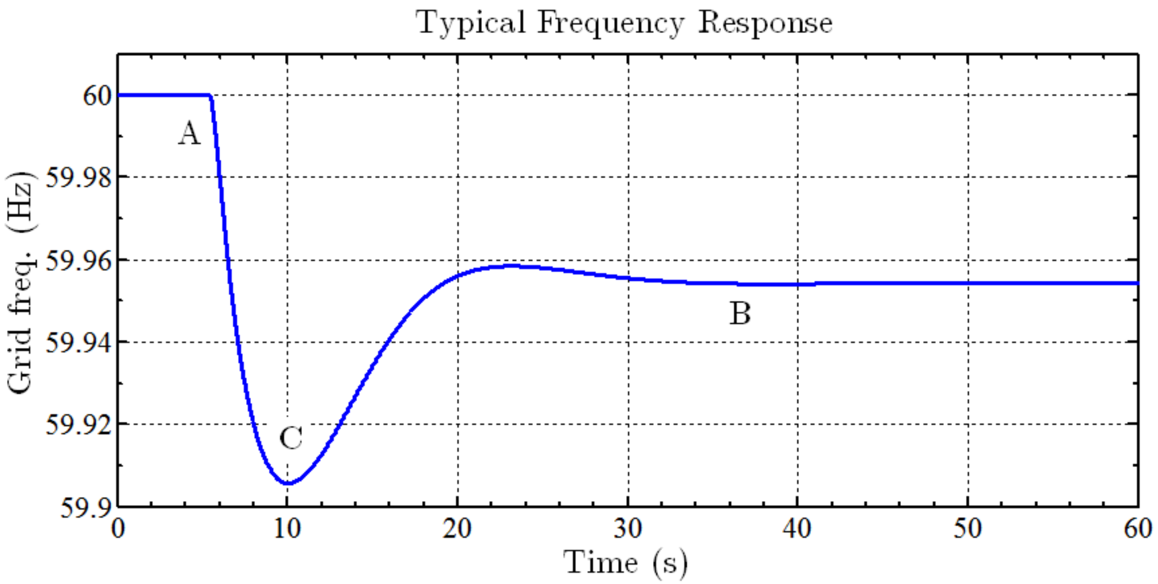
Photo courtesy of GE Renewable

Enabling Type-3 WTG for Advanced (Network) Control

- Currently most WTGs do not perform “network” control
  - Active power: maximum power output
  - Reactive power: constant power factor
- Many control inputs: pitch, rotor speed, converter current outputs, power setpoints
- A WTG has many internal control loops, many optimization calculations/approximations, and control modes (for example, reactive power control)
- Often an added external control implemented inappropriately is cancelled out by the built-in internal loops
- Investigate how to use WTG for frequency control

Frequency Control Overview

- Frequency
  - visible throughout the entire power system
  - reflects the balance of generation and load
  - needs to be kept within a tight range
- Investigate primary control frequency in first 60 seconds after unit trip



Typical frequency response after a loss of a large unit

Key factors:

- **A - Rate of Change of Frequency (ROCOF)**
- **B - Settling frequency**
- **C - Frequency nadir**

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Frequency Control in Systems with High Renewable Penetration

The main concern is renewable generation (like WTG) has less or no inertia contribution, and thus primary frequency response will deteriorate.

There are currently discussions of grid-forming and grid-following systems. We assume that AC generators (hydraulic turbines) are available.

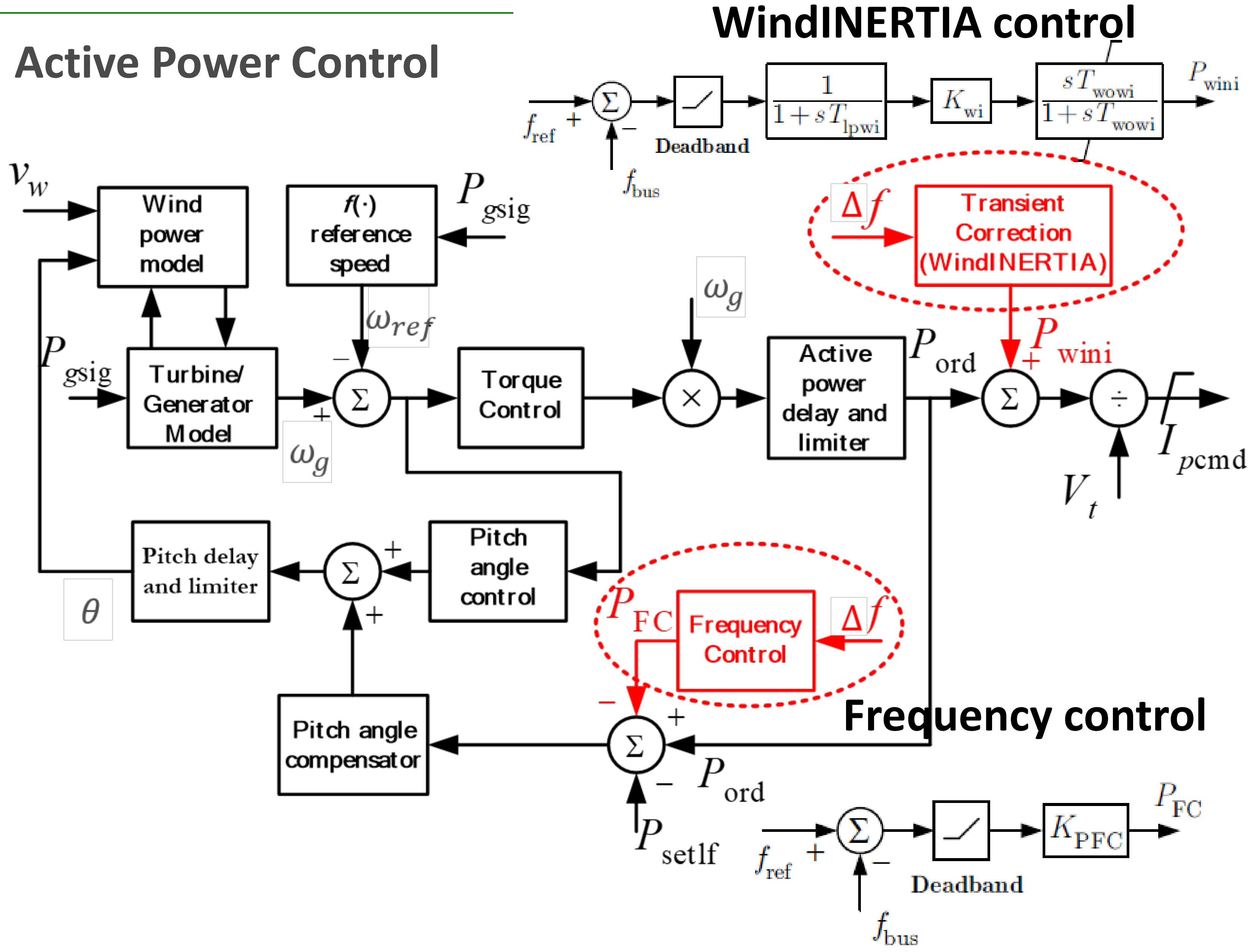
Question – how to restore (or improve) the historical frequency response?

Design a controller to make WTGs responsive to frequency fluctuations:

- Controller should restore the settling frequency → need for wind to have an active power headroom.
- Controller should help with the frequency nadir and RoCoF → make the WTG response as fast as the power-electronics interface allows it (which is faster than conventional generation)

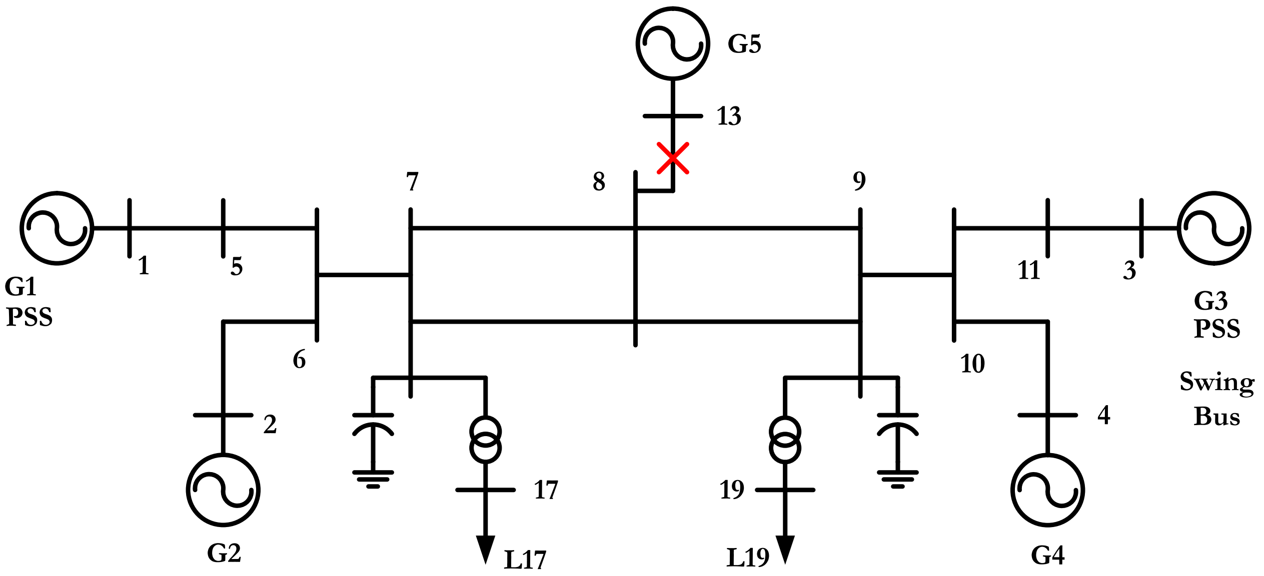
Frequency Control and Wind Generation

- Intentionally pitch the blades to spill power and create a headroom
- ***Frequency control (governing)***: pitch angle made to respond to frequency variations
- ***Transient correction (inertia emulation)***: Control signal added to the power order signal (to the converter model) to boost the WTG power output immediately



Frequency Control Test System

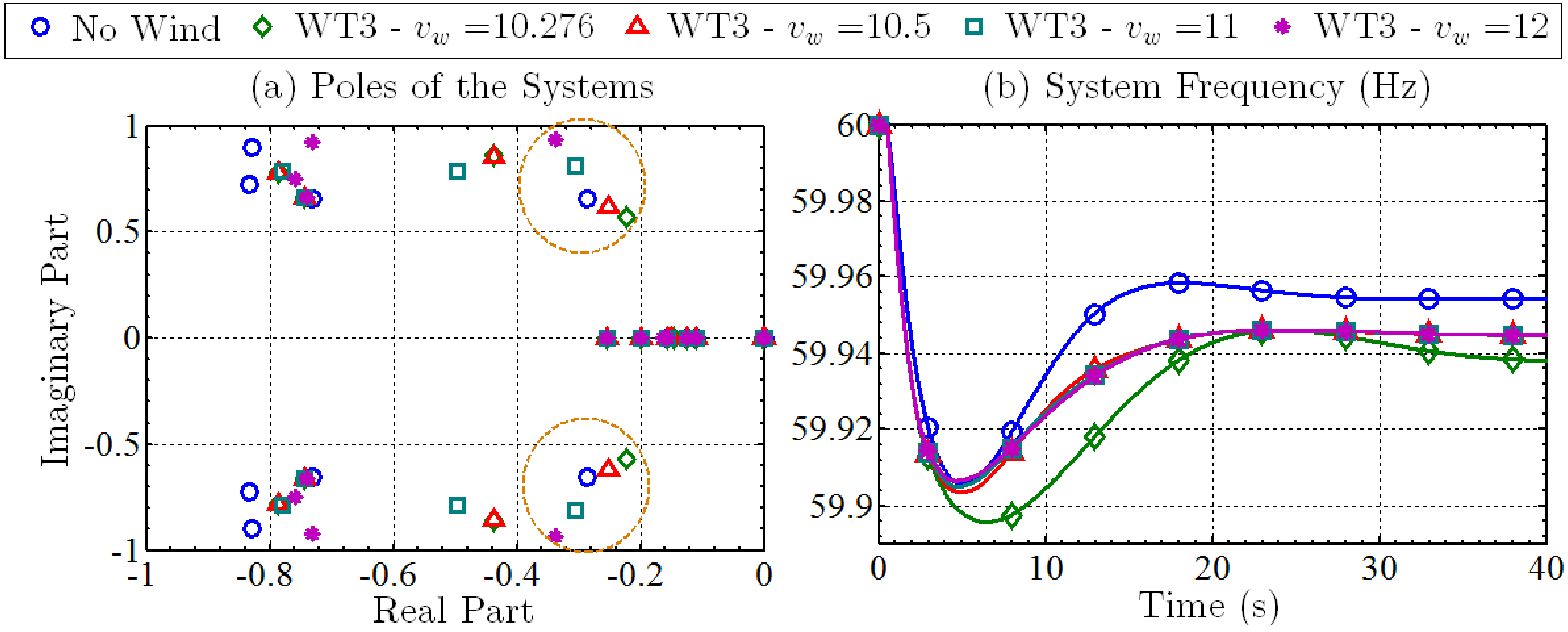
- Test system: Modified version of the two-area, four-machine system.



- Loss of generation simulated by tripping generator 5 (loss of ~4% total generation) in the middle of the transfer path
- One of the conventional generator replaced by Type-3 WTG: 25% penetration
- Study effects of system parameters

Type 3 WTG Response – Nominal Control System

- **Loss of generation event was simulated for different wind speeds**



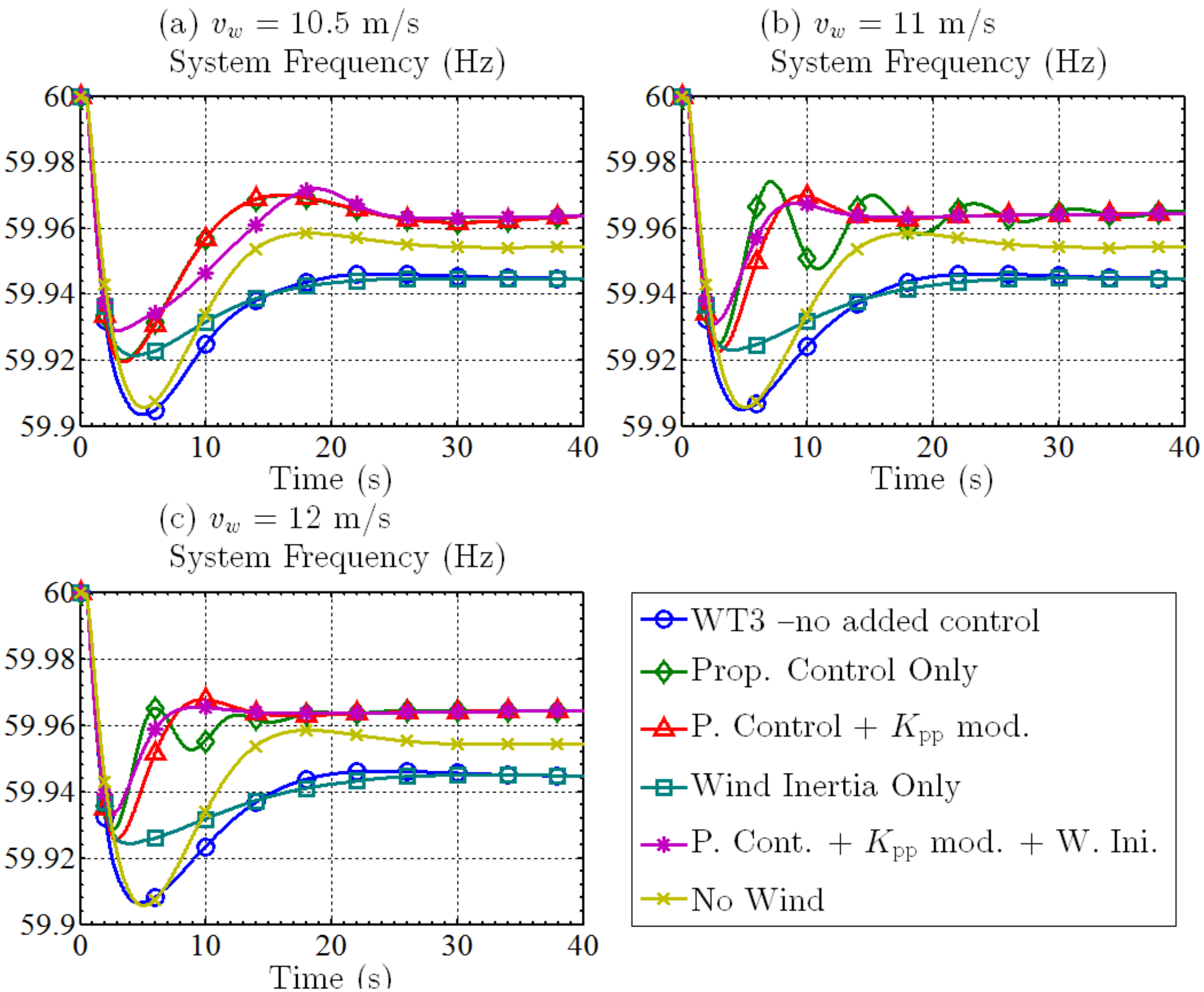
- **Result: integrating wind deteriorates the system frequency response – confirmation of previous results.**

WTG Frequency Controller Design

- Frequency control (governing) action
  - Implemented as a proportional controller with a deadband (similar to conventional generation control)
  - Sensitivity analysis was performed to tune the controller gain to ensure stability at all wind velocity conditions
  - A single parameter of the WTG (K_{pp}) tuned to damp the oscillations from other control loops
  - Proportional gain constant adjusted for satisfactory frequency response
- Transient gain (inertia emulation)
  - To improve the frequency nadir
  - No attempt to run the rotor at a *higher* (non-optimal) speed

Proposed Controller Performance

- **Comparison of various control design for 25% of wind generation**



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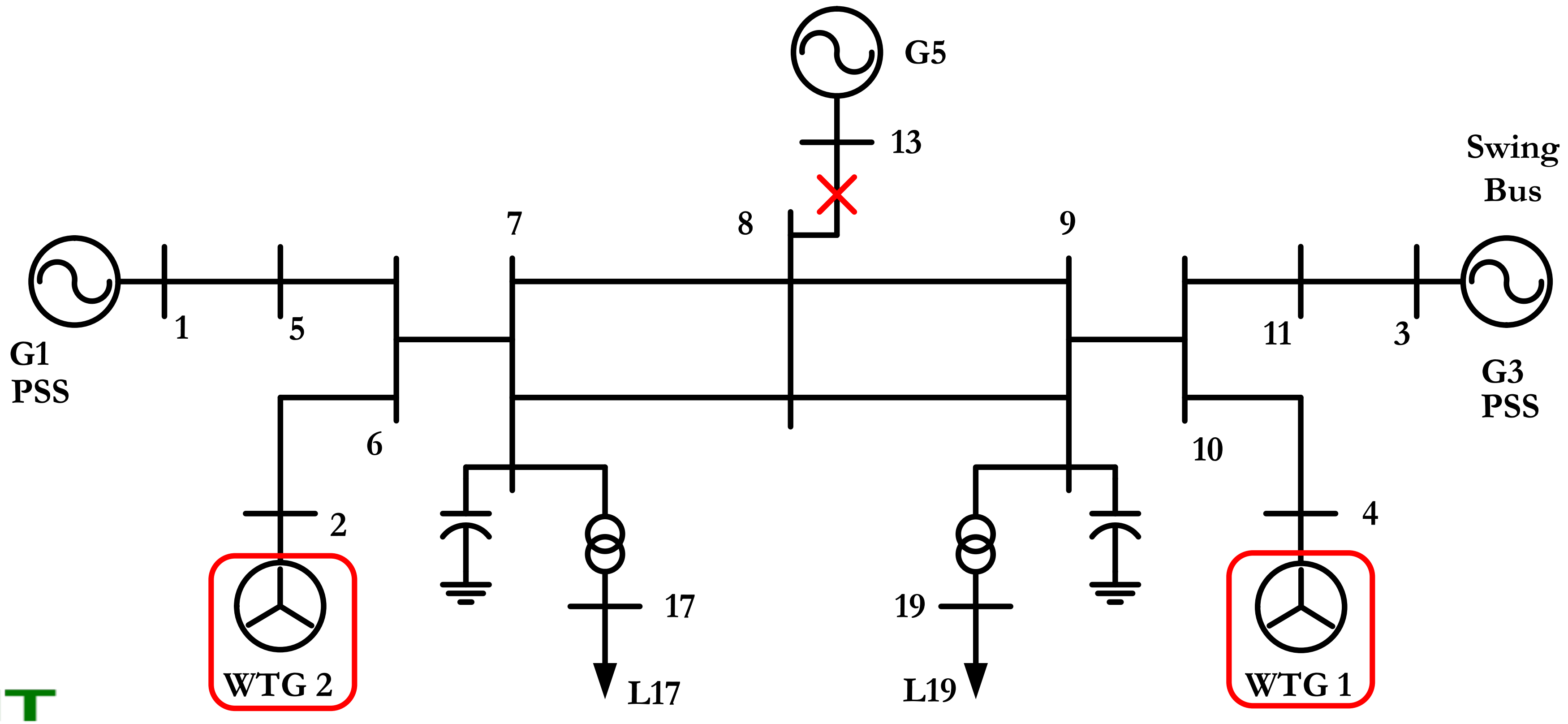
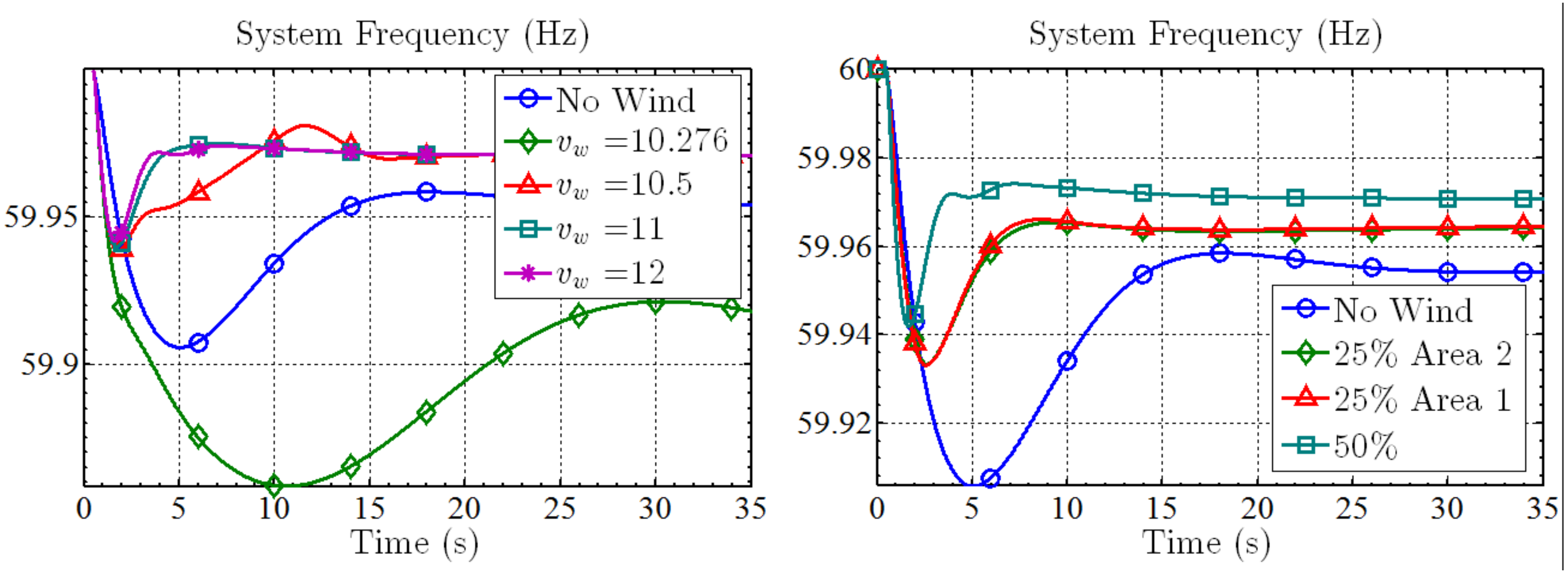
Increased Wind Penetration

- Proposed control was validated in the test system for a wind penetration of 50%, with the same generation trip event
- Generators at Bus 2 (Area 1) and Bus 4 (Area 2) replaced by Type-3 WTGs



50% Wind Penetration Control Performance

- **Proposed control implemented in each of the WTG**



- **50% of wind unresponsive to frequency has severe impact**
- **Enabling frequency control in WTGs improves considerably the frequency response**

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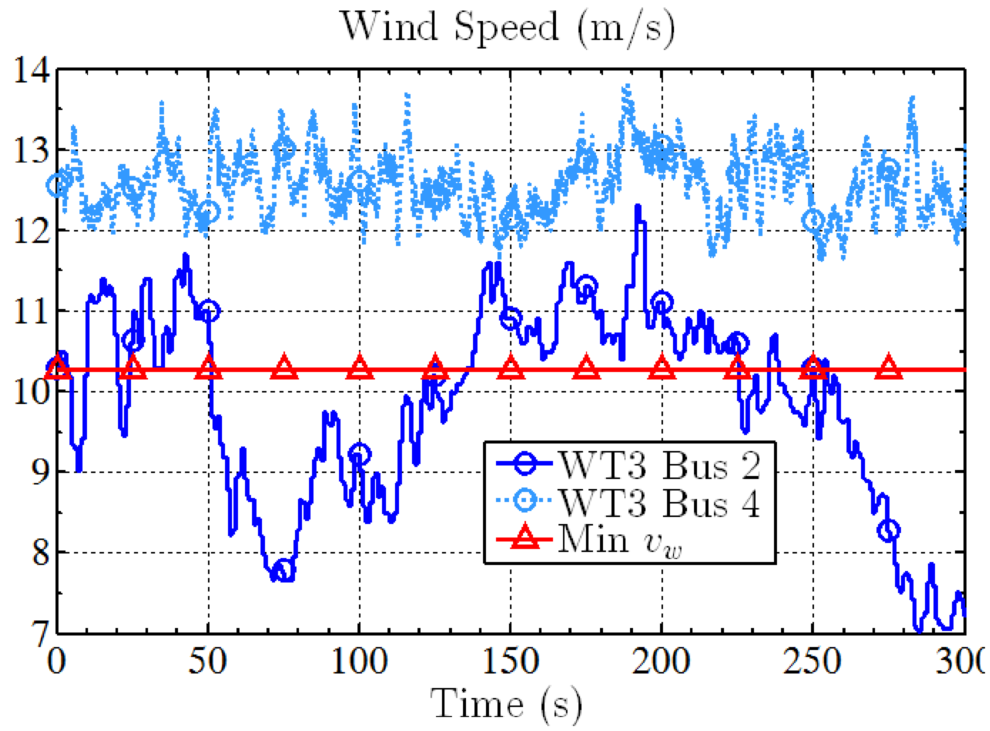
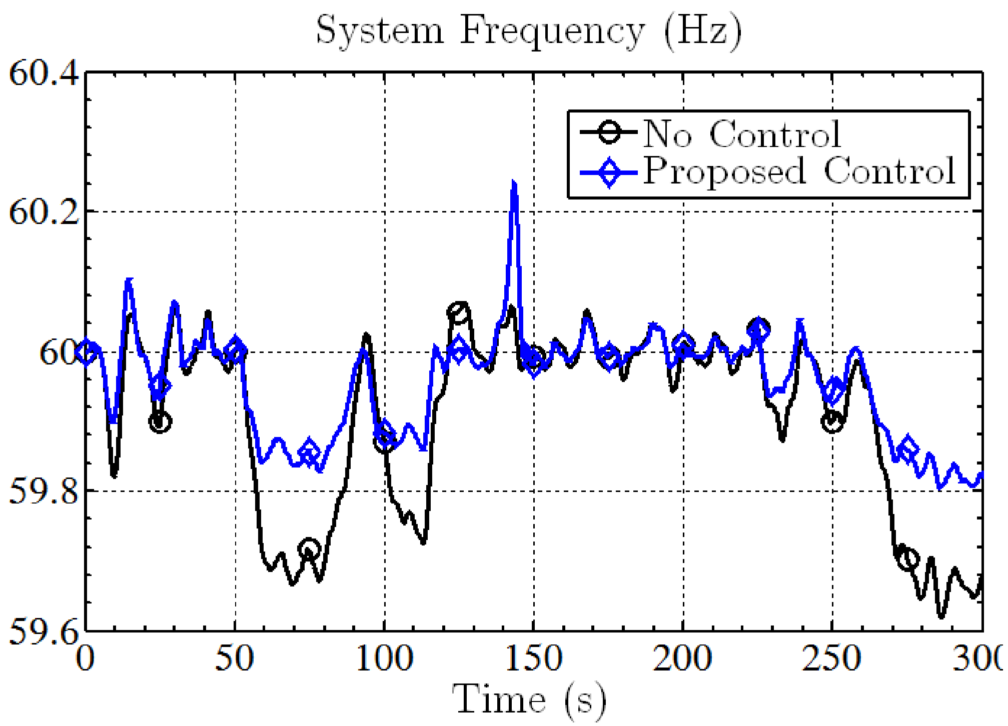
Variable Wind Speed Control Performance

The proposed controller was tested for the 50% wind penetration scenario with variable wind speeds

- WTG at Bus 2 is a simulated wind profile (Weibull distribution).
- WTG at Bus 4 is a measured wind profile provided by GE.





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Secondary Frequency Control in Era of High Renewable Penetration

- Secondary frequency control
  - Return system frequency to nominal
  - Return inter-area flows to schedule
- Balancing Areas (BAs) are required to keep deviations at a minimum (to historical performance levels)
  - US Eastern Interconnection –> 7 BAs
  - US Western Interconnection – > 30 BAs
- High renewable penetration increases frequency and interchange flow variations
  - High variability
  - Reduced inertia
  - Increased energy Interchange between areas
- Additional regulation reserves necessary
  - Increase total costs
  - Increase energy cost and locational marginal prices (LMPs)

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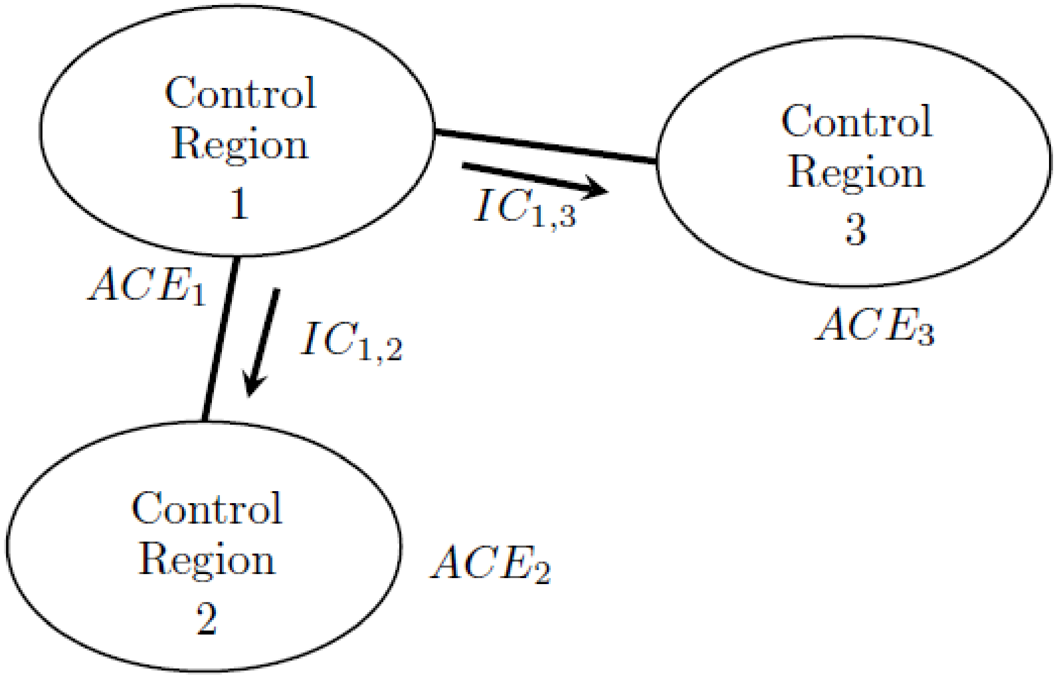
Area Control Error (ACE)

- ACE is used for secondary frequency regulation, defined as

$$\mathbf{ACE} = -\boldsymbol{\beta}\boldsymbol{\Delta f} - \boldsymbol{\Delta IC}$$

- ACE takes into account frequency and interchange deviations, where $\boldsymbol{\beta}$ is estimated system frequency response
- Each Balancing Area responsible for its own ACE
- NERC performance measures CPS1 and CPS2 require ACE to be close to 0 (NERC)



- Loss of generation in an area will make its ACE negative but ACE in other areas will not be affected
- The remaining generators in the affected area have to increase their power output to make up the power lost and return ACE to 0

Proposed AGC - Rationale

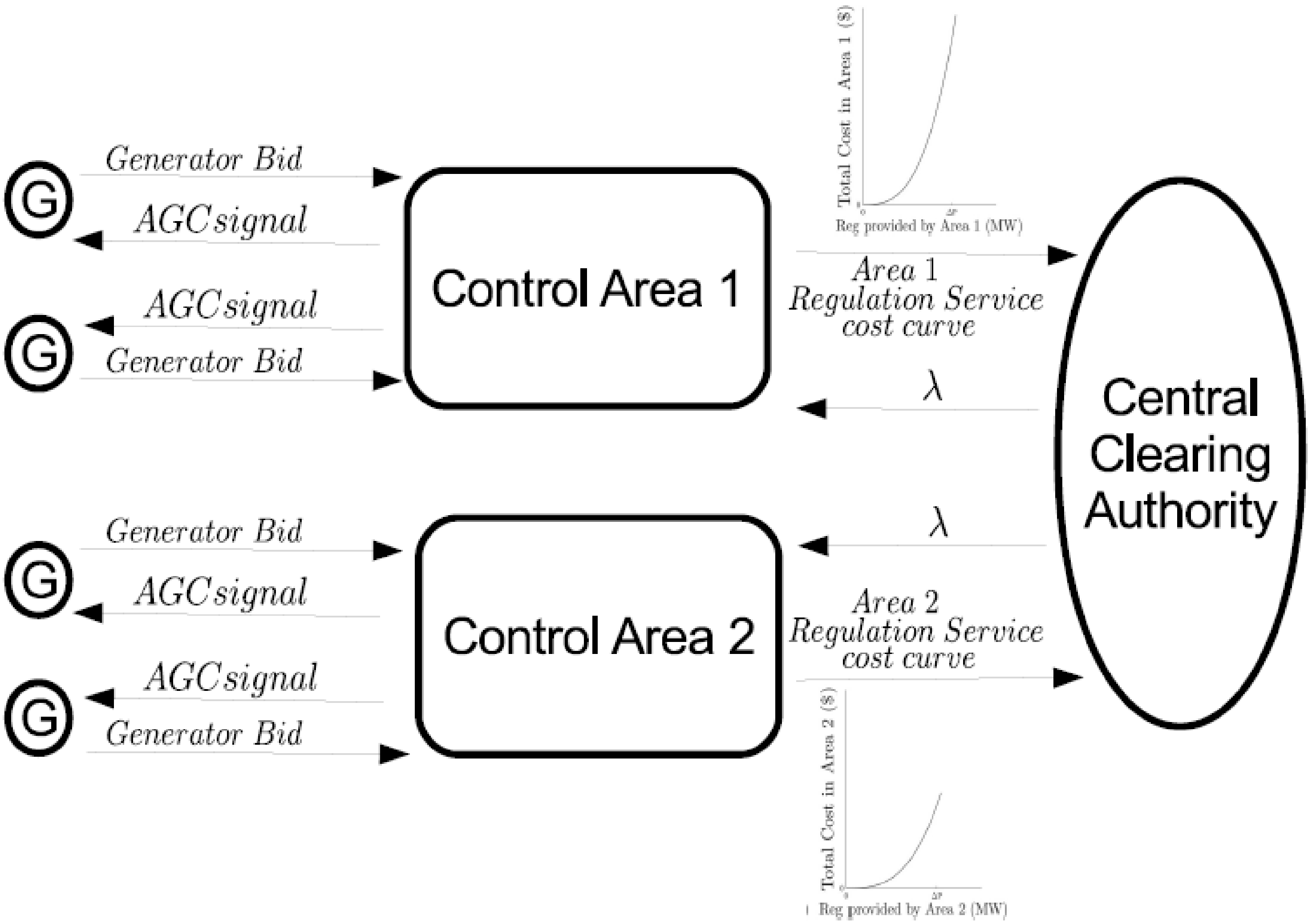
- A study for NYISO indicates a need to increase regulation services in 2030 aimed at 50% renewable energy
- Cost of additional regulation services can potentially be reduced if they can be secured from neighboring Balancing Areas
- *Objective*: implement the proposed strategy with minimum changes in the decentralized structure of the current AGC coordination
- *Approach*: Add an additional term to form an extended ACE signal to allow for a more economical solution

$$ACE_{ext} = -\beta_i \Delta f \; - \left(\Delta IC_i - P_{mod,i}\right)$$

  such that the total cost of regulation is minimized
- The E-AGC concept proposed by Liu and Ilic (2012 IEEE PES GM) has the same motivation (use less expensive resources from neighboring control regions). The E-AGC system requires more complex communication.

Determine $P_{mod,i}$ AGC

- Control across multiple Balancing Areas
- Minimize communication
- Protect privacy of all information exchanged
- Can be done distributive with a Central Clearing Authority requiring very little information



Determine $P_{mod,i}$ in AGC

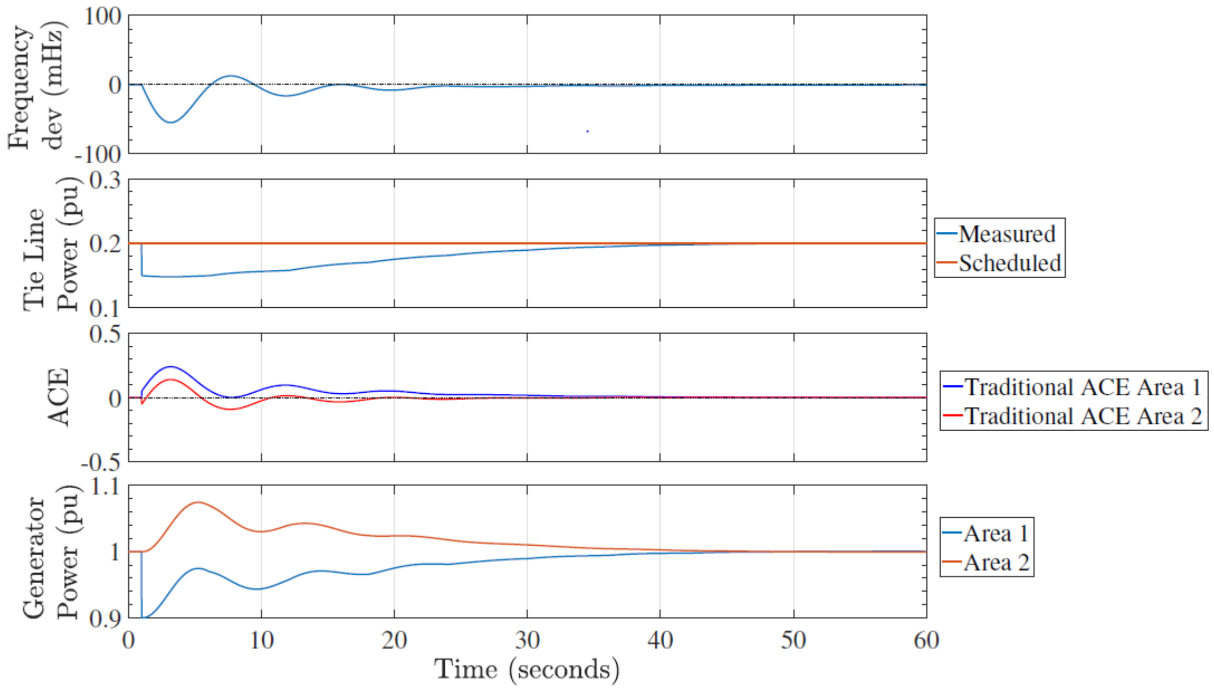
1. Each BA computes an aggregated regulation cost curve
   - Individual generator bids are not visible
2. Aggregated regulation cost curves are sent to Central Clearing Authority
3. Central Clearing Authority combines them to form a combined aggregated regulation cost curve
4. Determines Marginal Regulation Price
5. Each area dispatches generators up to marginal regulation price
6. *Also possible to implement as distributed control*

Simulation in a 2 Area System

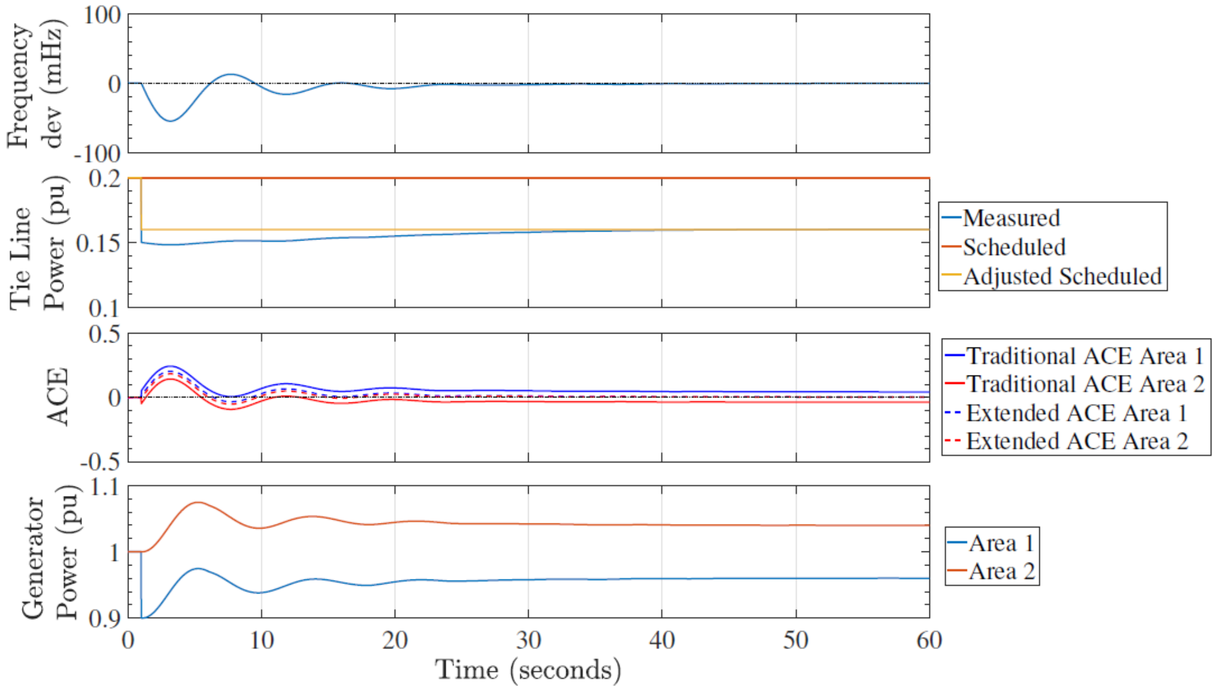
- 2-Area system with a single tieline
- 2 Generators participate in AGC
  - G1 in Area 1
  - G3 in Area 2
- Loss of generator in Area 1

	Area 1	Area 2
Power generation (pu)	1	1
Load (pu)	0.8	1.2
Scheduled export (pu)	0.2	−0.2

Traditional AGC

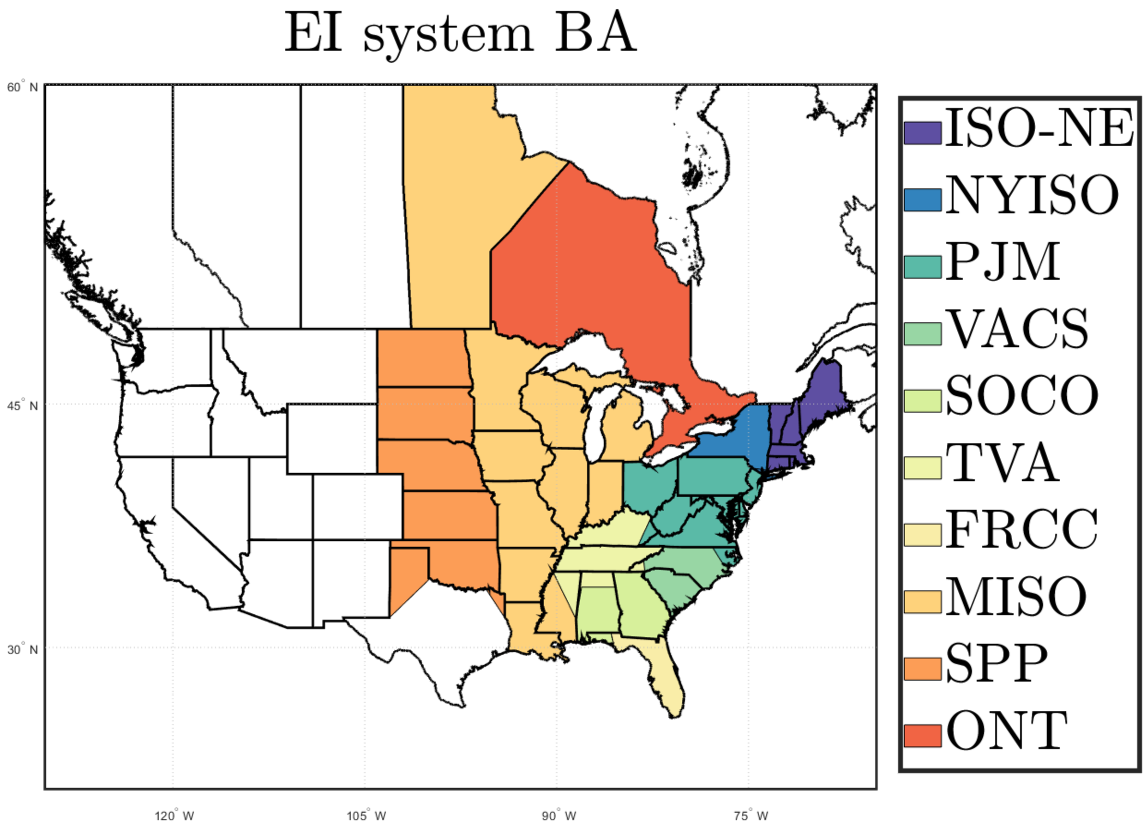


Extended AGC



Simulation of Large Systems with Renewables

- Simulate 528-Bus eastern interconnection
- Using CURENT Large Scale Test Bed
- Include scenarios with >50% wind penetration
- 10 interconnected Balancing Areas



Summary

- WTG can effectively use blade pitch to provide frequency regulation in the system, provided that some headroom is available; the frequency control functions can be incorporated into existing WTG controllers
- High renewable penetration will increase demand for frequency control
  - Sharing frequency control resources across Balancing Areas can lower cost of AGC and can be accomplished with minor modification to ACE

Acknowledgements

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