

# Hierarchical Coordinated Control of Wind Energy Resources and Storage for Electromechanical Stability Enhancement of the Grid

Chaitanya Baone, Chris DeMarco, Bernie Lesieutre, Yehui Han

Underlying Technical Concept: Seek a rigorous control design method for a long-standing practice in power systems. When multiple, distributed elements share wider system objective, distribute responsibility by available control response speed & limits.

Consider analogy to practice in voltage control:

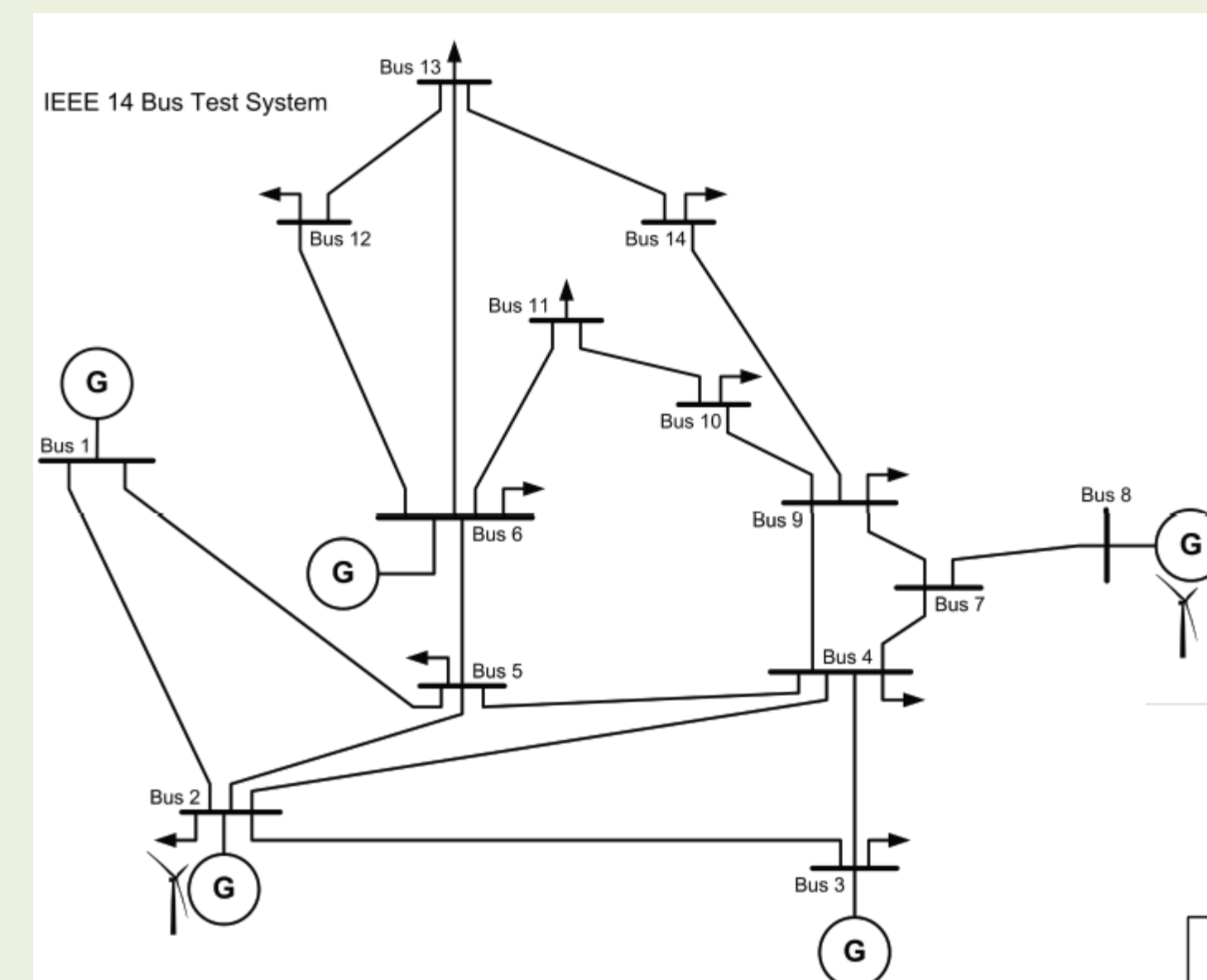
- Large magnitude actions from slow responding devices (switched capacitors);
- Fast response actions from devices with smaller limits on control magnitude (e.g., limited “dynamic” Vars, from exciters, or SVCs).

**High Level Goal for Future Grid Enable Frequency Control and Stability Enhancement Contributions from Very Diverse Technologies (Wind and Storage)**

## Deliverables:

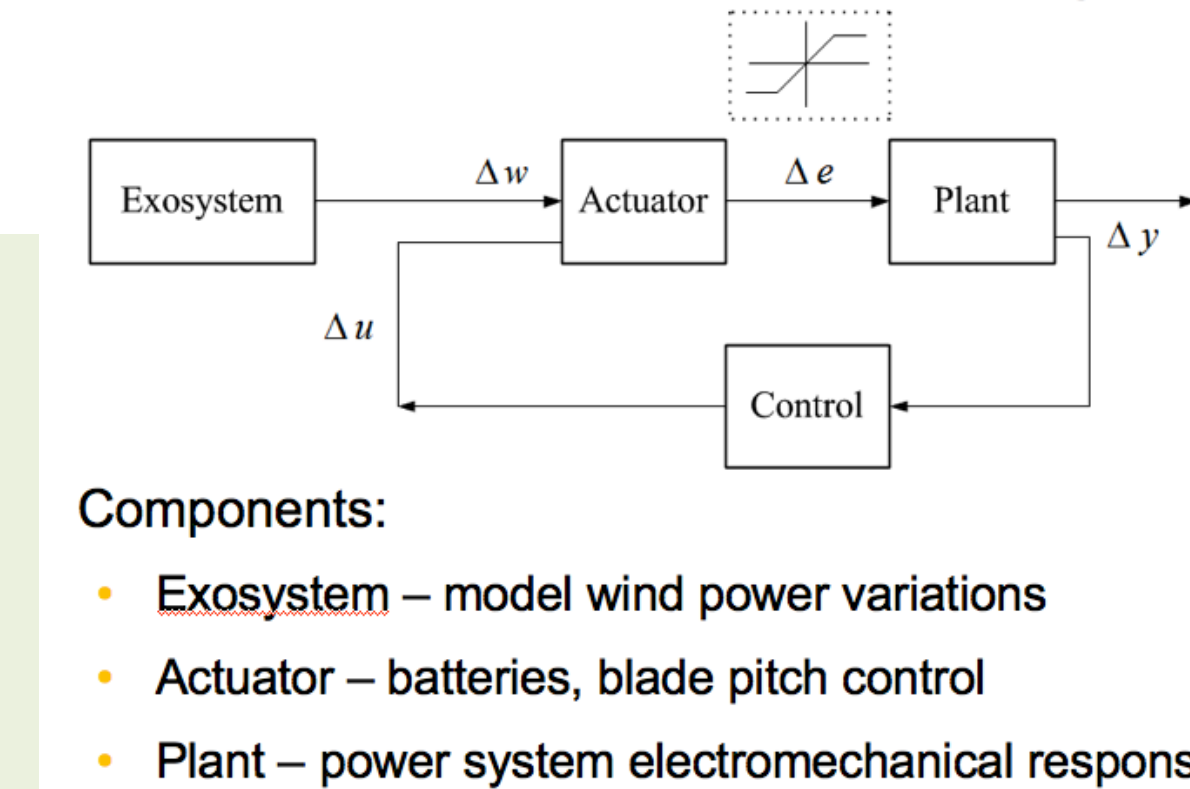
- 1) Optimal LQ-based state feedback design for: (a) slow-acting wind turbine blade pitch control; coordinated with (b) fast battery power output.
- 2) Design explicitly respects hard limits such as blade pitch range, power & energy bounds on battery.
- 3) Integrated with local observer design, to produce dynamic estimate of state (as used by controller) from small number of PMU measurements.

## Illustrative Example



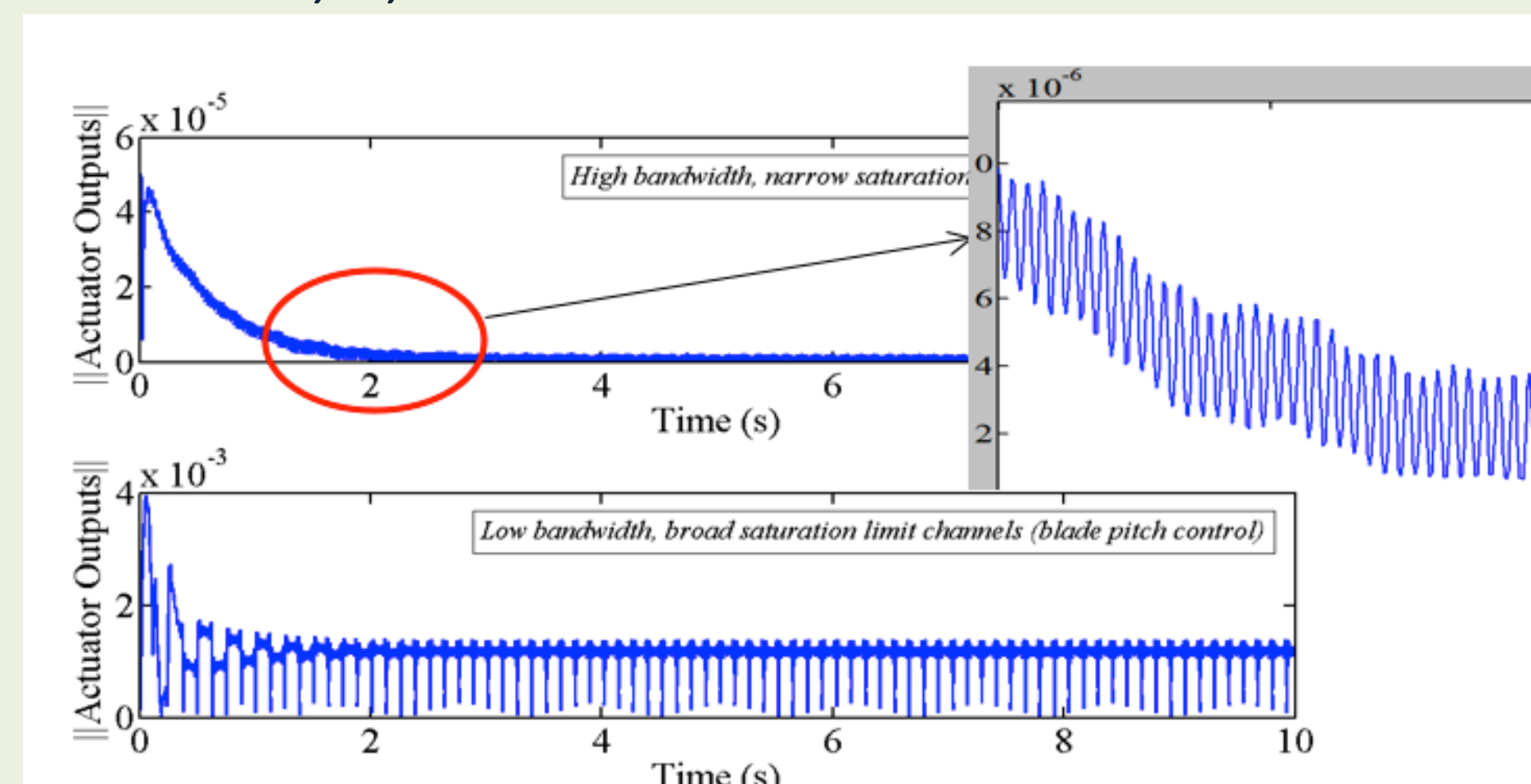
Generators @ buses 2 & 8  
WECC wind turbine model;  
Fast battery control supplements traditional synchronous generator output at buses 1, 3, 6

Conceptual Block Diagram for Controller/Observer Design



Components:

- Exosystem – model wind power variations
- Actuator – batteries, blade pitch control
- Plant – power system electromechanical response



Batteries (top) provide much smaller magnitude control action, quickly “recentering” on zero, but with higher frequency content. Saves turbine drivetrain (bottom) from higher frequency stresses.

This “limit-respecting” control is a Linear Quadratic (LQ) based design. Standard form uses full state feedback - NOT PRACTICAL!

To the rescue... state observers and the separation principle – establish use of estimated states works as well in full state feedback.

Key Question: Can small number of measurements suffice? (PMU’s are cheap, but low-latency, highly secure communication links expensive). For range of test systems, observability analysis answers a firm YES!!

Practical Implication: Local controllers use local measurement, plus one or two remote PMU measurements. State estimate “drives” LQ controller.

## Technical Background/Detail

Method rests on results of Saberi *et al* (2000). LQ design penalizes state limit violation, w/ “built-in” model for disturbances (here = wind variation)

Consider the linear system

$$\dot{x} = Ax + B\sigma(u) + E_w w \quad (1)$$

$$\dot{w} = Sw \quad (2)$$

$$y = Cx + D_y w \quad (3)$$

$$\sigma(s) = [\bar{\sigma}(s_1), \bar{\sigma}(s_2), \dots, \bar{\sigma}(s_m)]^T$$

$w$  – “exosystem” (fast time scale wind variation)

$x$  – states of plant,  $u$  – input subject to saturation

$\bar{\sigma}(s)$  – saturation function(s)

- Seeking control of form:  $u = F_{\mu,\epsilon} x + [\Gamma - F_{\mu,\epsilon} \Pi] w$   
Solve Algebraic Riccati Equation (ARE)

$$P_\epsilon A + A^T P_\epsilon - P_\epsilon B B^T P_\epsilon + Q_\epsilon = 0$$

$$Q : (0, 1] \rightarrow \mathbb{R}^{n \times n}, Q_\epsilon > 0, \frac{dQ_\epsilon}{d\epsilon} > 0$$

Solution to the ARE is a unique positive definite  $P_\epsilon$  that is monotonically increasing with respect to  $\epsilon$

Then, state feedback matrix is given by

$$F_{\mu,\epsilon} = -(\mu + 1) B^T P_\epsilon$$

As sufficient conditions to ensure regulation, there should exist matrices that solve

$$\begin{cases} \Pi S = A \Pi + B \Gamma + E_w \\ 0 = C \Pi \end{cases} \text{Regulator equations}$$

Sample publications:

[1] C. L. DeMarco and C. A. Baone, “Smart grid control design methods for distributed energy storage in frequency regulation markets,” in Proceedings of the 18th IFAC World Congress, Milan, Italy, Sept. 2011.

[2] C. A. Baone and C. L. DeMarco, “From each according to its ability: Distributed grid regulation with bandwidth and saturation limits in wind generation and battery storage,” to appear, IEEE Transactions on Control Systems Technology.

## Payoff in a Nutshell

Let wind resources, supplemented by very modest amounts of storage, contribute to control objectives historically reserved for synchronous generators (e.g., enhancing stability).

In contrast to prior work, design optimally for capabilities and limits of wind machines and batteries themselves.

Don’t try to force wind and storage to behave just like (“mimic” inertia of) traditional machines.