Wide-Area Control of Power System Networks using Synchronized Phasor Measurements

Theory, Challenges, and Open Problems

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CMU Electricity Conference 2014

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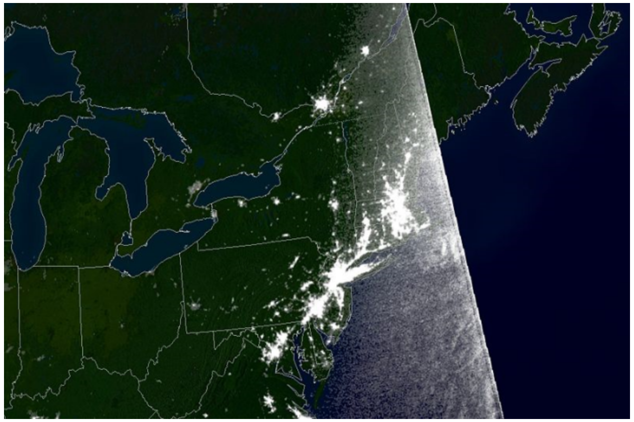
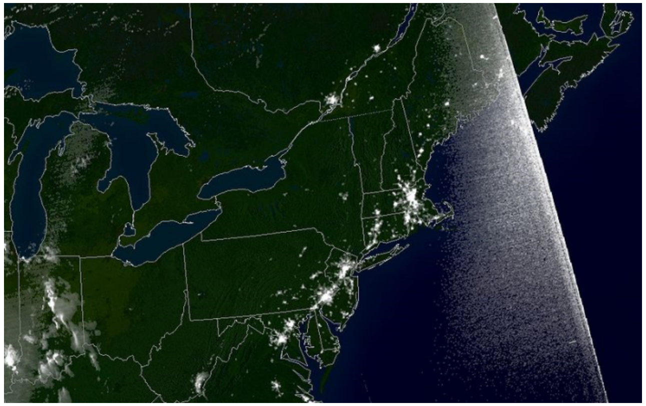
Pittsburgh, February 6, 2014

Main trigger: 2003 Northeast Blackout

NYC before blackout



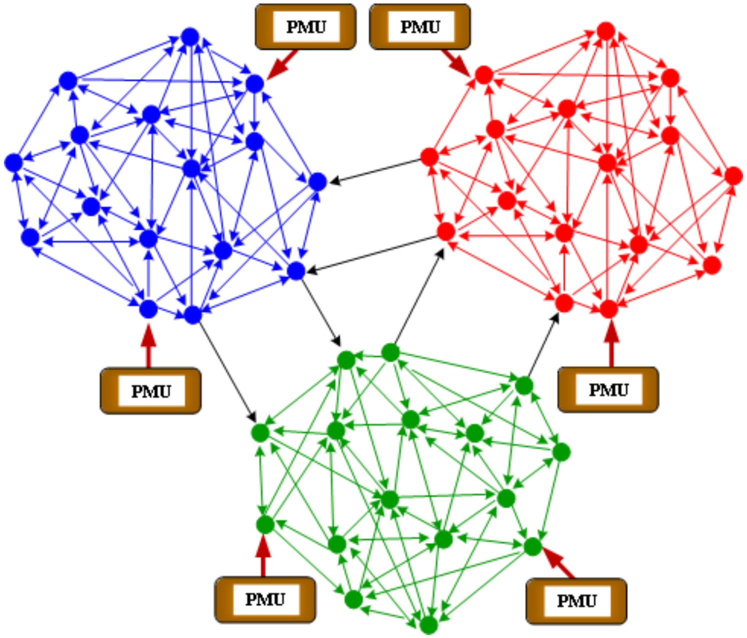
NYC after blackout



2 Main Lessons Learnt from the 2003 Blackout:

1. Need significantly higher resolution measurements

⇨ From traditional SCADA (System Control and Data Acquisition) to PMUs (Phasor Measurement Units)



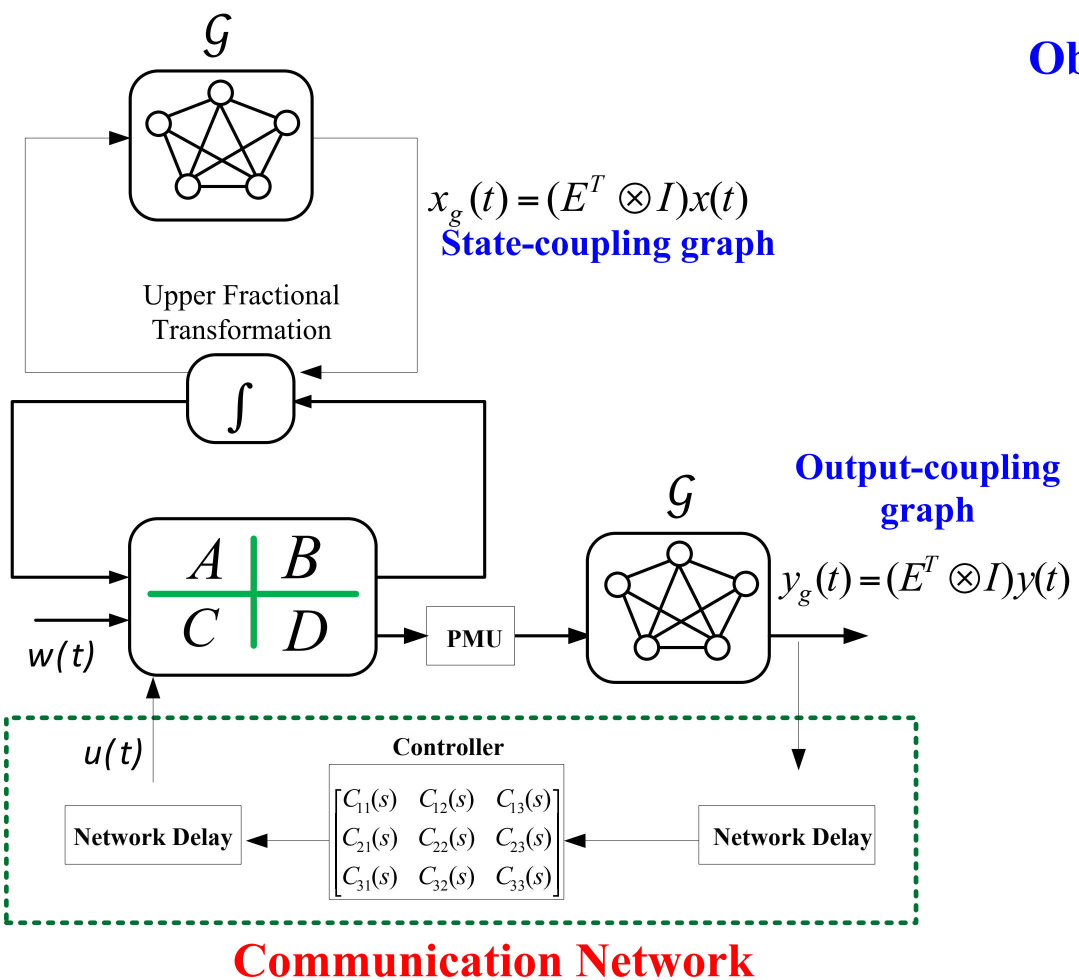
2. Local monitoring & control can lead to disastrous results

⇨ Coordinated control instead of selfish control

Hauer, Zhou & Trudnowsky, 2004
Kosterev & Martins, 2004

What is Wide-Area Control?

Coordination of multiple sensors with multiple actuators to satisfy a global control goal in a distributed fashion over a secure communication network



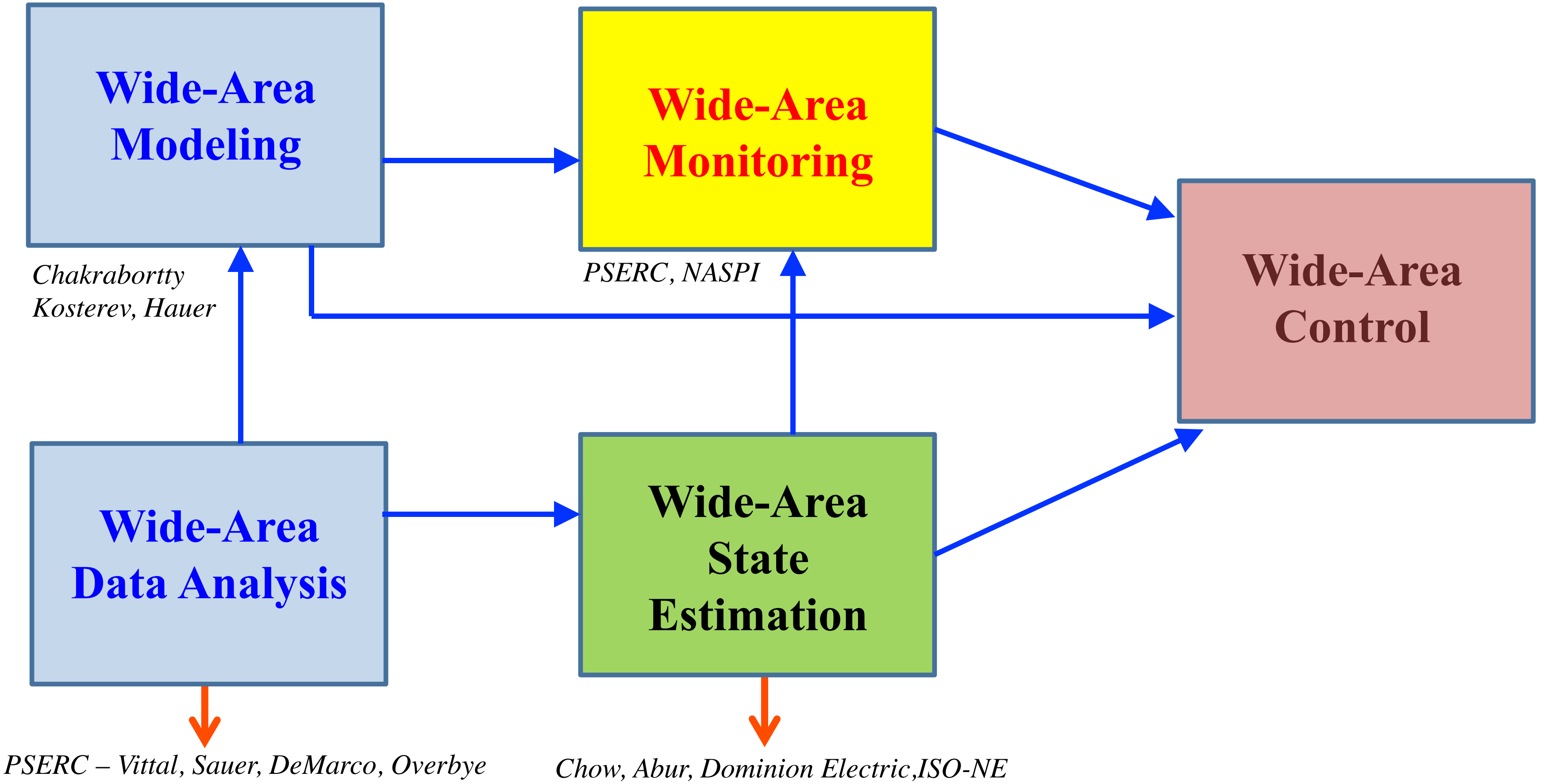
Objective of this talk is to formulate some of these control goals

Three Obvious Challenges

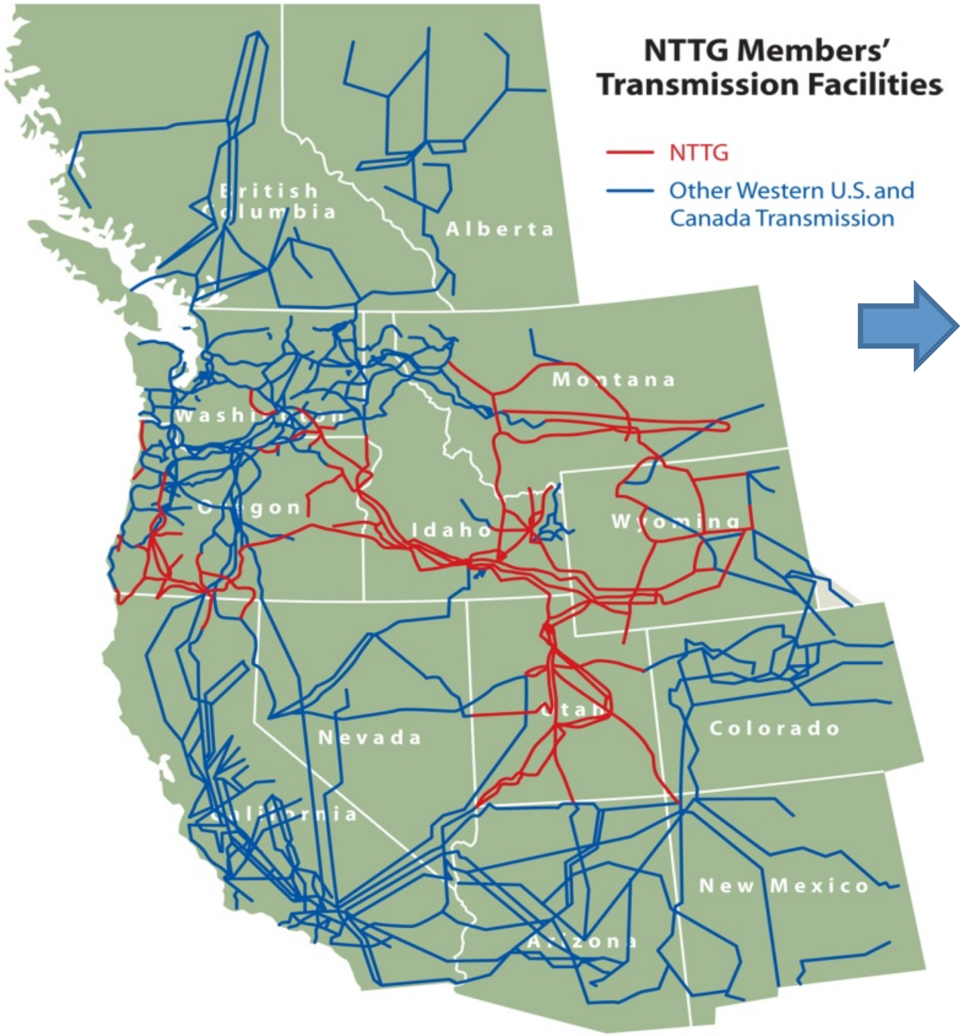
- Time-scale for computation
  Real-time computing, fast numerical algorithms – Big Data, parallel computing
- Communication uncertainties
  Multi-cast, routing, jitters, cyber-security – Competition & data privacy, game theory
- Control - Robust, output-feedback, distributed – Arbitrated communication control

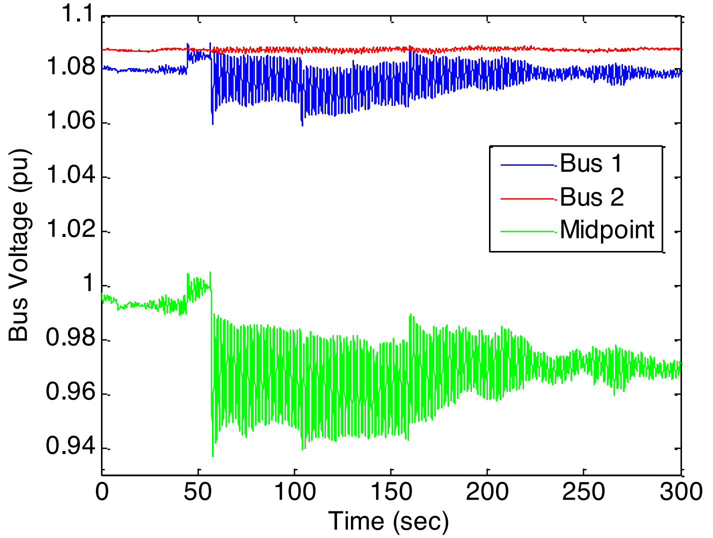
Building Blocks of Wide-Area Control

- WAC is **not** just a "controller design" problem
- Many building blocks before addressing the control problem



Wide-Area Modeling





Massive volumes of PMU data from various locations

Dynamic models of the grid at various resolutions

$$\dot{x} = f(x, y, \theta)$$
$$0 = g(x, y, \theta)$$

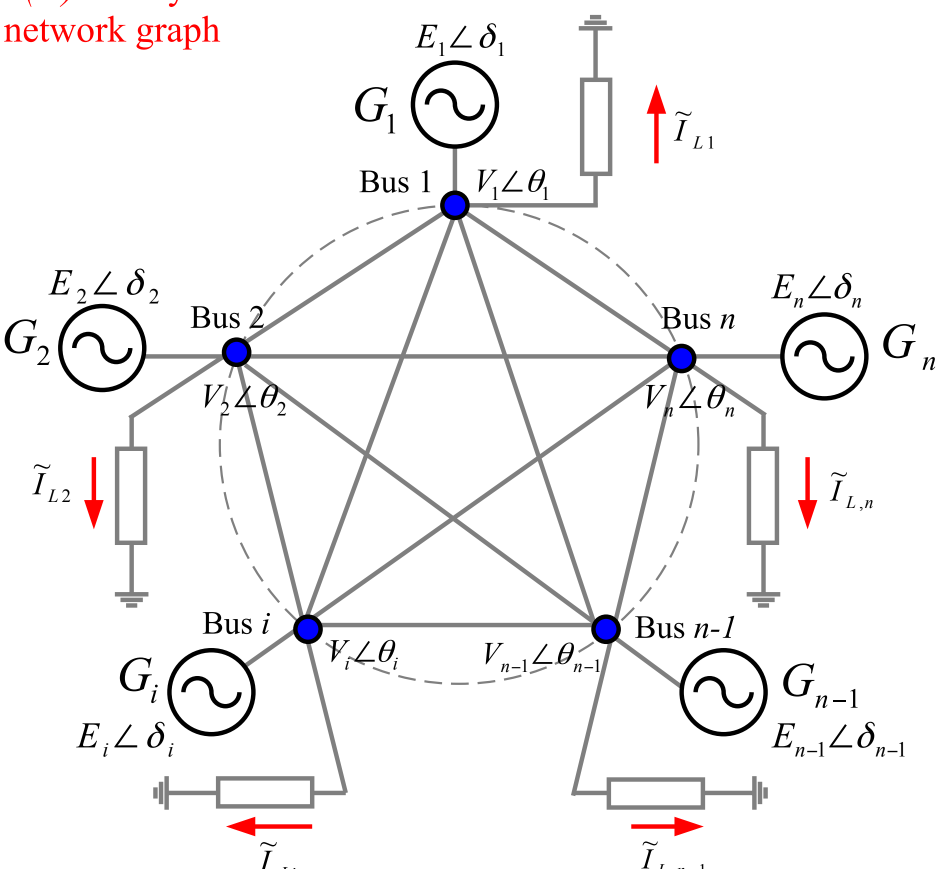
- Periodic updates of the grid models is **imperative** for reliable monitoring & control

• Grid Dynamic Model

$$\begin{bmatrix}\Delta\dot{\delta}\\ M\Delta\dot{\omega}\\ \Delta\dot{E}\end{bmatrix} = \begin{bmatrix}0 & I & 0\\ -L(G) & -D & -P\\ K & 0 & J\end{bmatrix}\begin{bmatrix}\Delta\delta\\ \Delta\omega\\ \Delta E\end{bmatrix} + \underbrace{\begin{bmatrix}0\\ \mathrm{col}_{i=1\,(1)n}(\gamma_i)\\ \mathrm{col}_{i=1\,(1)n}(\rho_i)\end{bmatrix}}_{\text{due to load}} + \begin{bmatrix}0 & 0\\ 0 & I\\ I & 0\end{bmatrix}\begin{bmatrix}\Delta P_m\\ \Delta E_F\end{bmatrix} \quad \textbf{...(1)}$$

L(G) = fully connected network graph

Controllable inputs



ΔP_m
- low bandwidth
- used mostly for AGC
- mechanical system wear and tear

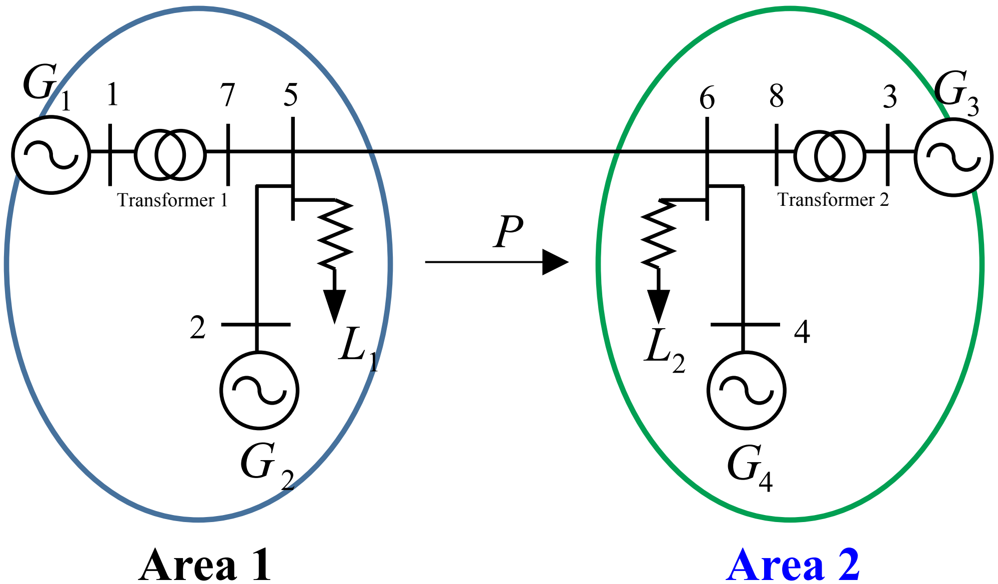
ΔE_F
- much higher bandwidth
- used for oscillation damping
- electrical input

Output Equation

$$y = \mathrm{col}_{i\in\mathcal{S}}(\Delta V_i,\, \Delta\theta_i). \quad \textbf{...(2)}$$

Model Reduction

- Time-scale separation leads to model reduction - fast oscillations vs inter-area oscillations
- When the network is divided into distinct areas:



Fast variable $$q_{ik} = \delta_{ik} - \delta_{1k}, \quad i = 1, 2, \ldots, n_k, \quad k = 1, \ldots, r$$

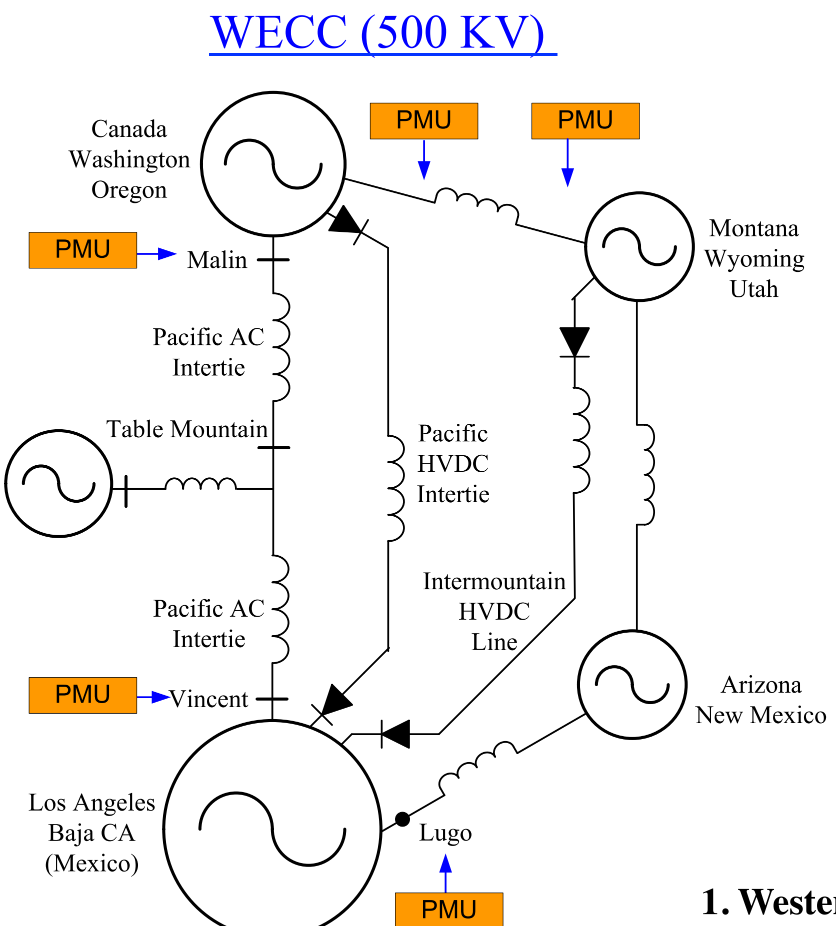
Slow variable $$p_k = \frac{\sum_{i=1}^{n_k} M_i^k \delta_i^k}{\sum_{i=1}^{n_k} M_i^k}, \quad k = 1, 2, \ldots, r$$

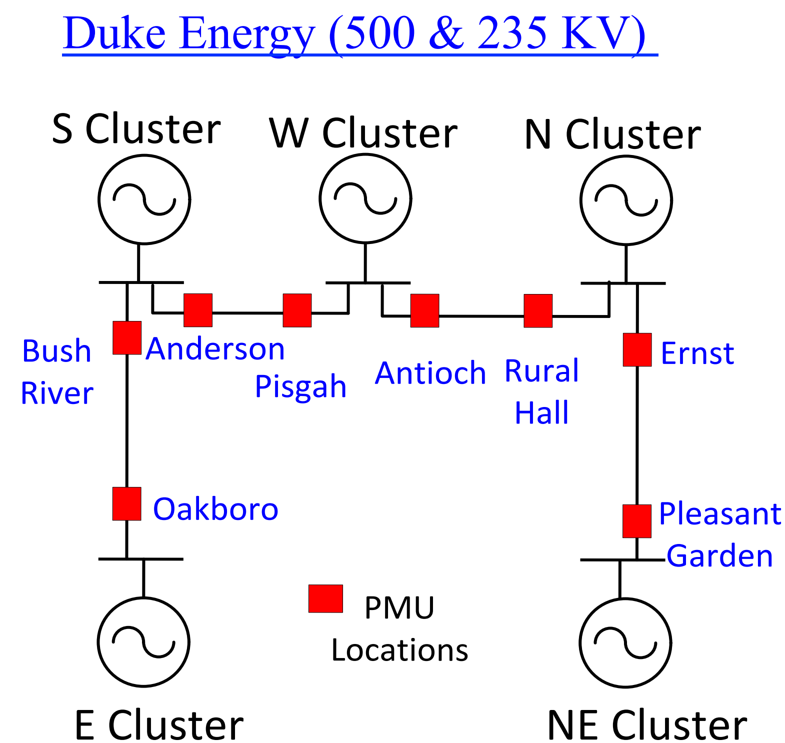
Singular Perturbation Model $$\frac{dp}{dt_s} = A_{11} p + A_{12} q, \qquad \varepsilon \frac{dq}{dt_s} = A_{21} p + A_{22} q$$

Reduced-order Model: $$\frac{dp}{dt_s} = (A_{11} - A_{12} A_{22}^{-1} A_{21}) p + B_{eq} u$$ ⇒ State-matrix is Laplacian!

Chow and Kokotovic, 1979

Examples of Inter-area Clustered Models





1. **Western cluster** – Mitchel River, Antioch, Marshall, Pisgah, Tucksagee, Shiloh, North Greenville
2. **Eastern cluster** – Harrisburg, Peacock, Allen, Lincoln, Oakboro
3. **Northern cluster** – Ernst, Sadler, Rural Hall, North Greensboro
4. **North-eastern cluster** – Pleasant Garden, East Durham,
5. **Southern cluster –** Shady Grove, Anderson, Hodges, Bush River

Problem # 1

Given $y = \mathrm{col}_{i \in \mathcal{S}}(\Delta V_i,\, \Delta\theta_i)$. develop output-only algorithms to identify the parameters of the *inter-area* model

$$\frac{dp}{dt_s} = \underbrace{(A_{11} - A_{12}A_{22}{}^{-1}A_{21})}_{}\,p + B_{eq}u \qquad \text{....(3)}$$

Equivalent generator parameters
+ Equivalent topology

Notice underlying structure for system identification

Open challenges:

1. Given $y(t)$, how do we know the *inter-area* model (3) is identifiable?
2. Which PMUs and what measurements will guarantee identifiability?
3. Is the PMU selection problem NP-complete?
4. Can ID be distributed across multiple local PDCs over a network?
5. If yes, which PMU data should go to which PDC?
6. How does penetration of renewable energy sources (such as wind and solar power) change the reduced-order model (3) and its identifiability

Graph-theoretic algorithms for network identifiability

$$\dot{x}(t,\theta) = A(\theta)x(t,\theta) + Bu(t),$$
$$y(t,\theta) = Cx(t,\theta).$$

Identifiability of parameter set (θ) means: $y(t,\theta_1) = y(t,\theta_2) \Rightarrow \theta_1 = \theta_2$

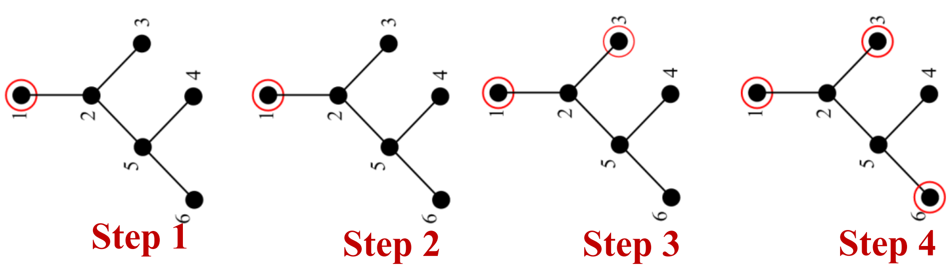
(Glover & Grewal, 1990)

How to interpret this from a graph-theoretic point?

- Geometric observability (min cover of the graph) does NOT imply identifiability

PMU at minimum cover ⇎ PMU needed for identifiability of edge weights

- We have recently developed sensor placement algorithms in tree networks that guarantee global identifiability: Relate Markov Parameters with algebraic properties of the Tree Laplacian



Ongoing work with Behzad Nabavi, and Pramod Khargonekar, 2014

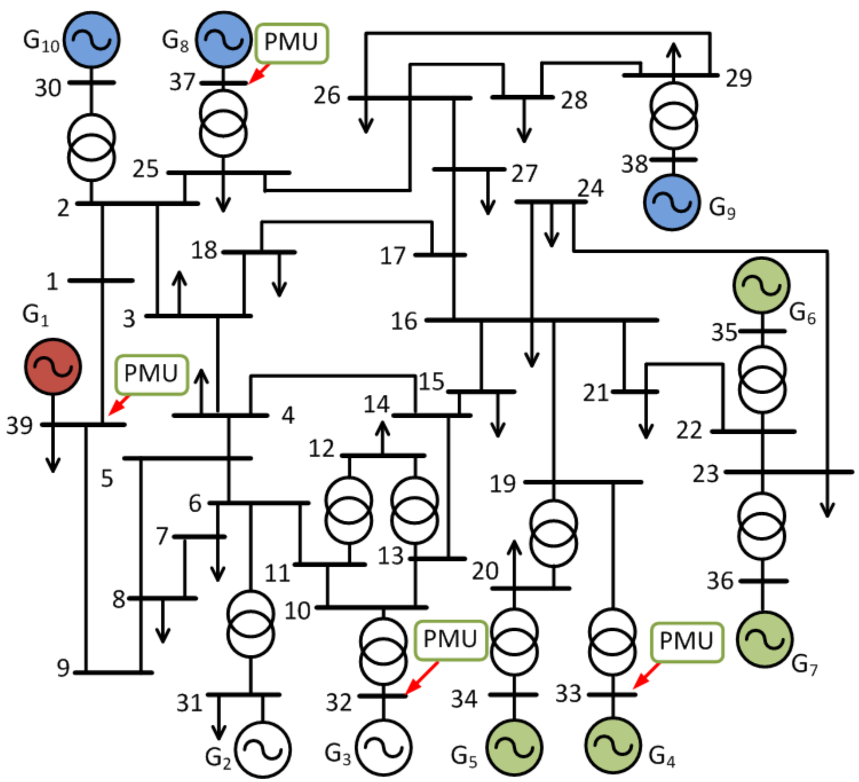
Hint for topology ID

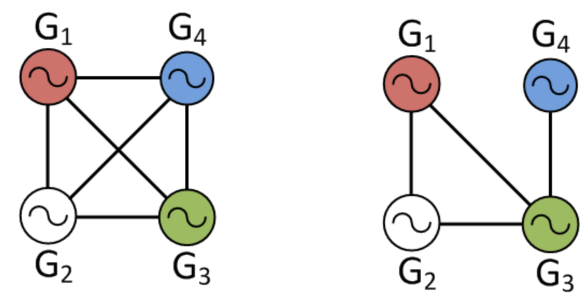
Extract slow oscillatory components of PMU data $y(t)$ using modal decomposition methods,
Then cast as a sparse optimization problem:

$$\min_{A_d, B_d} \frac{1}{2} \| X_i^{m+1} - A_{d_i} X^m - B_{d_i} u^m \|_2^2 + \lambda \sum_j | L^E_{ij} |$$

→ Convexify the problem as L_2-L_1 opt.

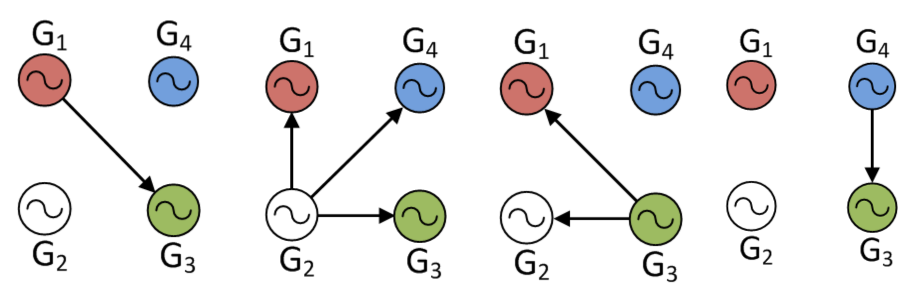
IEEE 39-Bus System





Linear LS **Nonlinear LS**

Decentralized Topology ID by each RTO



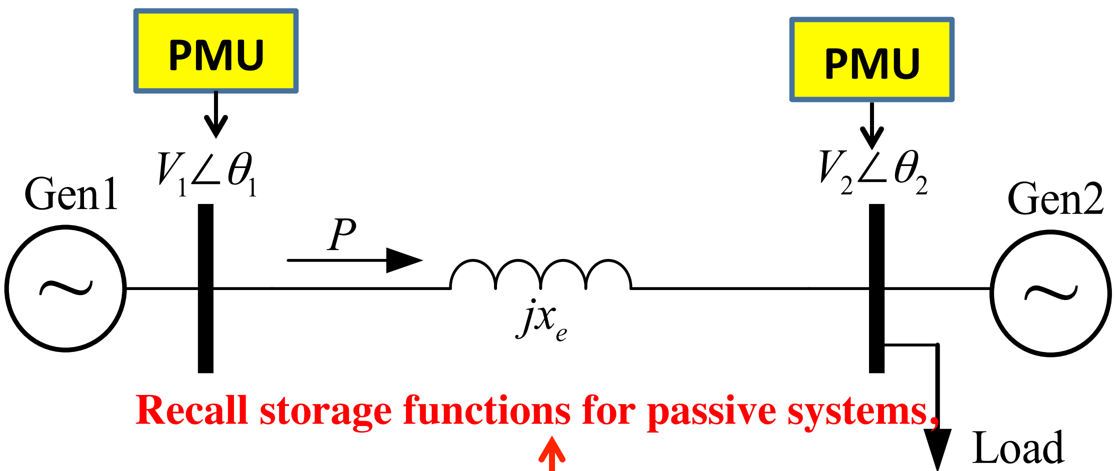
Area 1 **Area 2** **Area3** **Area 4**

Nabavi & Chakrabortty, ACC 2013

Wide-Area Monitoring Metrics

- There are commonly used metrics that operators like to keep an eye on
- Use wide-area models + PMU data to construct these metrics
- Example:

  Transient stability – Energy functions/ Lyapunov functions



Can be the reduced-order model

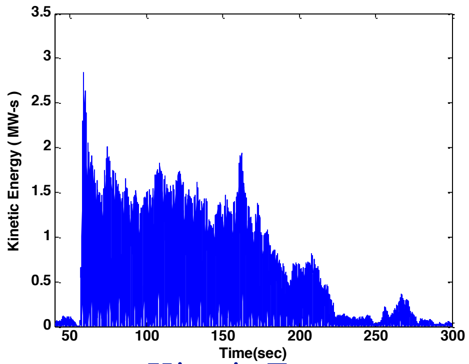
Recall storage functions for passive systems.

$$S = S_1 + S_2 = \sum_{j=1}^{n(n-1)/2} \int_{\delta_{ij}^*}^{z_j} \psi_j(k)\, dk + \sum_{j=1}^{n} \frac{M_j}{2} \xi_j^2$$

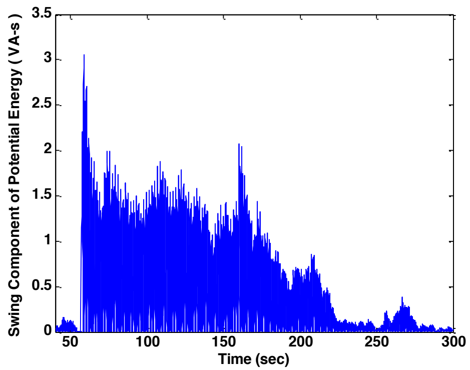
$$= \underbrace{\frac{E_1 E_2}{x_e'}\left[\cos(\delta_{op}) - \cos(\delta) + \sin(\delta_{op})(\delta_{op} - \delta)\right]}_{\text{Potential Energy}} + \underbrace{H\omega^2}_{\text{Kinetic Energy}}$$

Problem # 2

Given $y = \text{col}_{i \in \mathcal{S}}(\Delta V_i,\, \Delta\theta_i)$. develop real-time algorithms to estimate the energy function for the full-order or reduced-order model

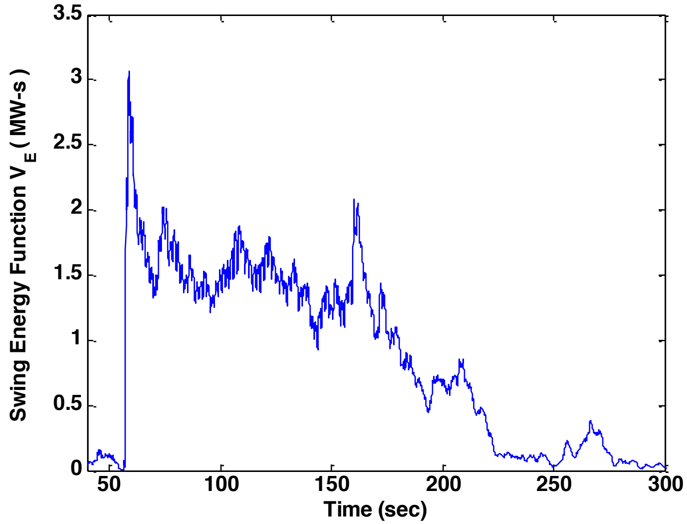


Kinetic Energy



August 4, 2000 event in WECC

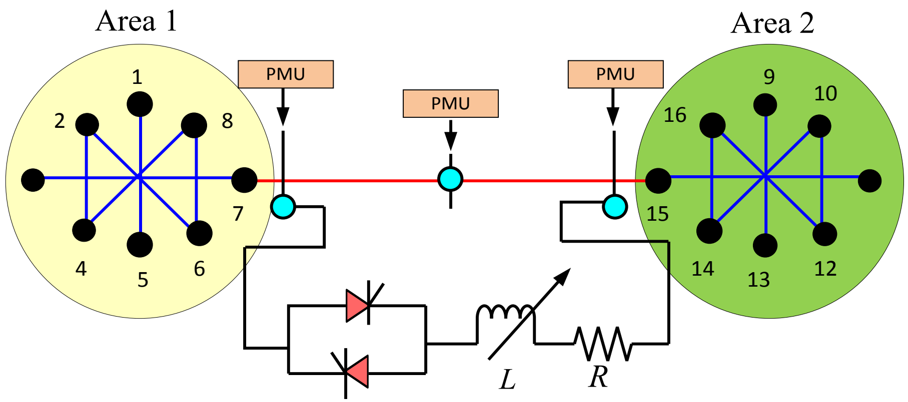
Total Energy = Kinetic Energy + Potential Energy

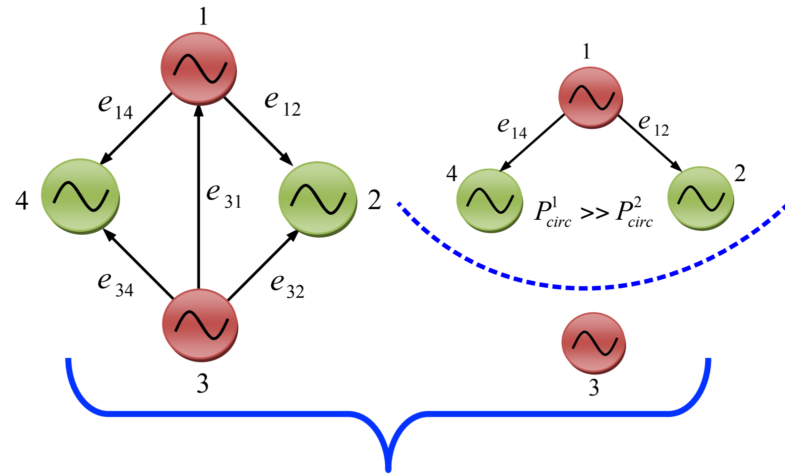


- Total energy decays exponentially – *damping stability*
- Total energy does not oscillate – *Out - of - phase osc.*

Given $y = \text{col}_{i \in \mathcal{S}}(\Delta V_i,\, \Delta\theta_i)$. design an optimal controller ΔE_f to minimize the energy function (or, *control Lyapunov function*) for the full-order or reduced-order model

Wide-Area Control Objectives





Smart Islanding – max flow min-cut

3 critical problems

- **Inter-area oscillation damping** – output-feedback based MIMO control design for the full-order power system to shape the closed-loop phase angle responses of the reduced-order model

- **System-wide voltage control** – PMU-measurement based MIMO control design for coordinated setpoint control of voltages across large inter-ties
  - FACTS controllers (SVC, CSC, STATCOM)

- **Controlled islanding** – use PMU data to continuously track ***critical cutsets*** of the network graph – i.e., min set of lines carrying max sets of dynamic power flows
- max-flow min-cut graph optimization

Problem # 3- Interarea Oscillation Damping

Consider the power system model

$$\begin{bmatrix} \Delta\dot{\delta} \\ M\Delta\dot{\omega} \\ \Delta\dot{E} \end{bmatrix} = \underbrace{\begin{bmatrix} 0 & I & 0 \\ -L(G) & -D & -P \\ K & 0 & J \end{bmatrix}}_{A} \begin{bmatrix} \Delta\delta \\ \Delta\omega \\ \Delta E \end{bmatrix} + \underbrace{\begin{bmatrix} 0 \\ \mathrm{col}_{i=1\,(1)n}(\gamma_i) \\ \mathrm{col}_{i=1\,(1)n}(\rho_i) \end{bmatrix}}_{\text{due to load}} + \begin{bmatrix} 0 & 0 \\ 0 & I \\ I & 0 \end{bmatrix} \begin{bmatrix} \Delta P_m \\ \Delta E_F \end{bmatrix}$$

$$y = \mathrm{col}_{i\in\mathcal{S}}(\Delta V_i,\, \Delta\theta_i).$$

Choose m generators for implementing wide-area control via ΔE_F. Let the measurements available for feedback for the j^{th} controller be $y_j(t)$. Let $Y(t,\tau) = [y(t-\tau_j)]$ where τ_j is signal transmission delay. Let τ be the vector of all such delays.

Define a performance metric $\mathcal{J}$ to quantify the closed-loop damping of the slow eigenvalues of A. Let $\mathcal{P}$ denote the set of all possible models resulting from parameter/structural variations in the system. Design an output-feedback dynamic controller $F(Y(t,\tau))$ that solves:

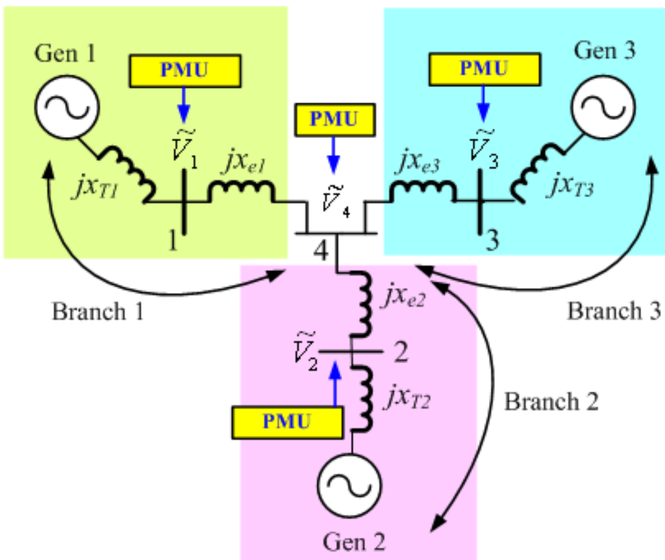
$$\min_{\mathcal{F}} \max_{\mathcal{P}} \mathcal{J}$$

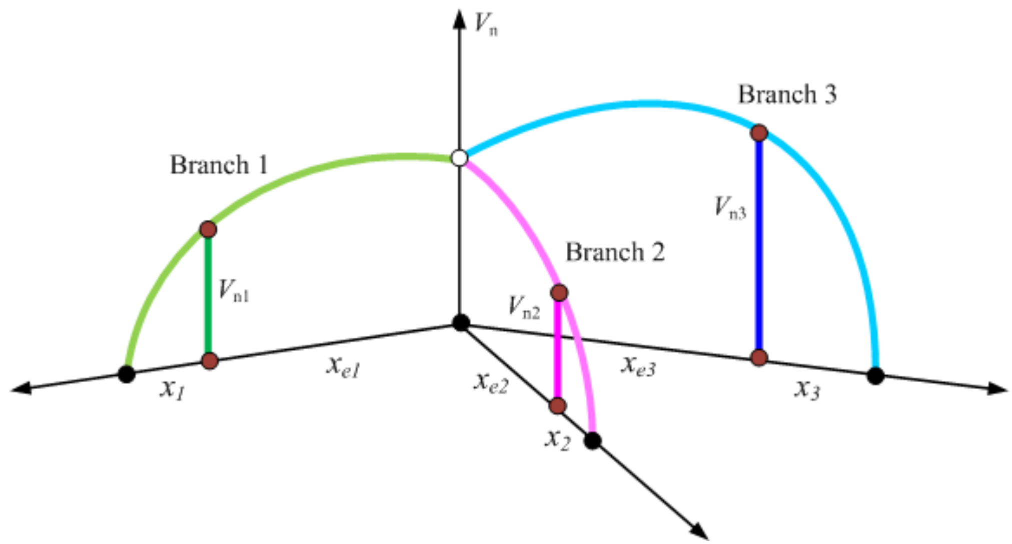
Hints of potential approaches:

1. H_∞ control defined over a network is an ideal choice, formulate LMIs
2. Distributed MPC, Co-operative game theory with communication cost & privacy constraints
3. Graph-theoretic control designs for shaping eigenvalues and eigenvectors *(Nudell & Chakrabortty)*

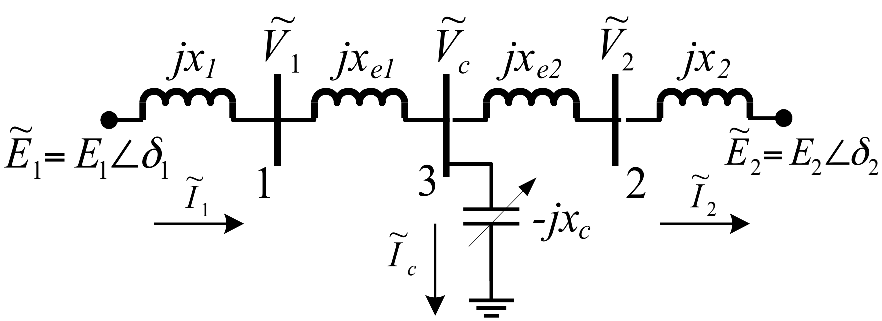
Voltage Control

- Key question: How does voltage vary spatially across a large grid?

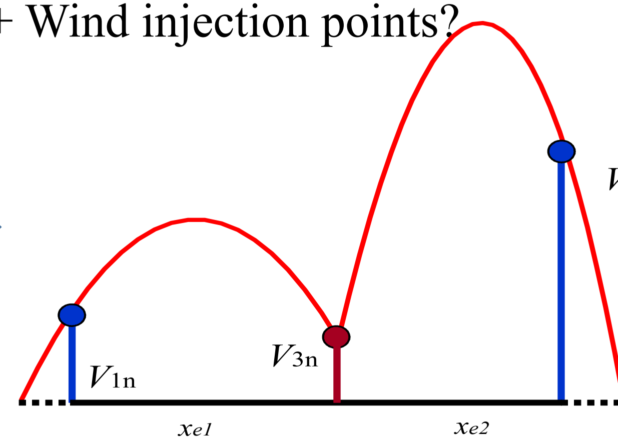




- How do voltage profiles change with FACTS control + Wind injection points?



SVC for bus voltage control



Voltage shoots up elsewhere

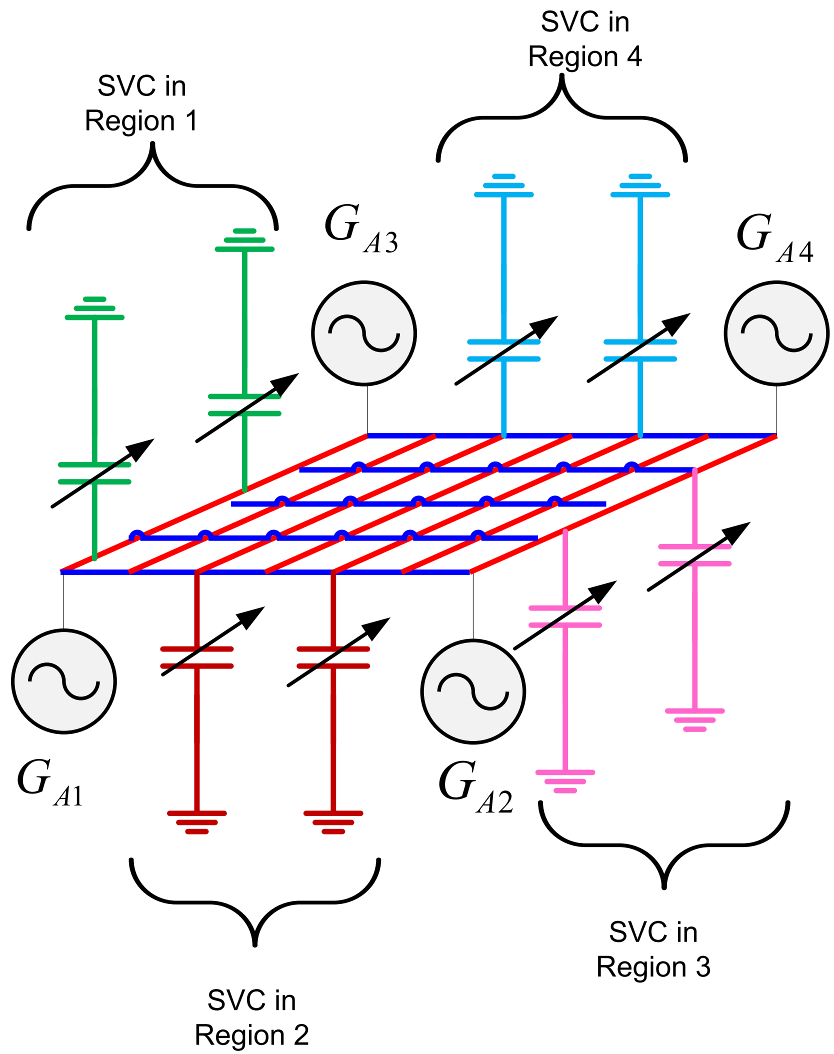
Problem # 4

Multivariable voltage control

Consider *m* SVCs and denote their control inputs as *u(t)*. Define a performance metric *J* that reflects the voltage deviation at all buses from their setpoints. Given PMU measurements *y(t)*, design an output feedback dynamic controller

$$u(t)=F(y(t))$$

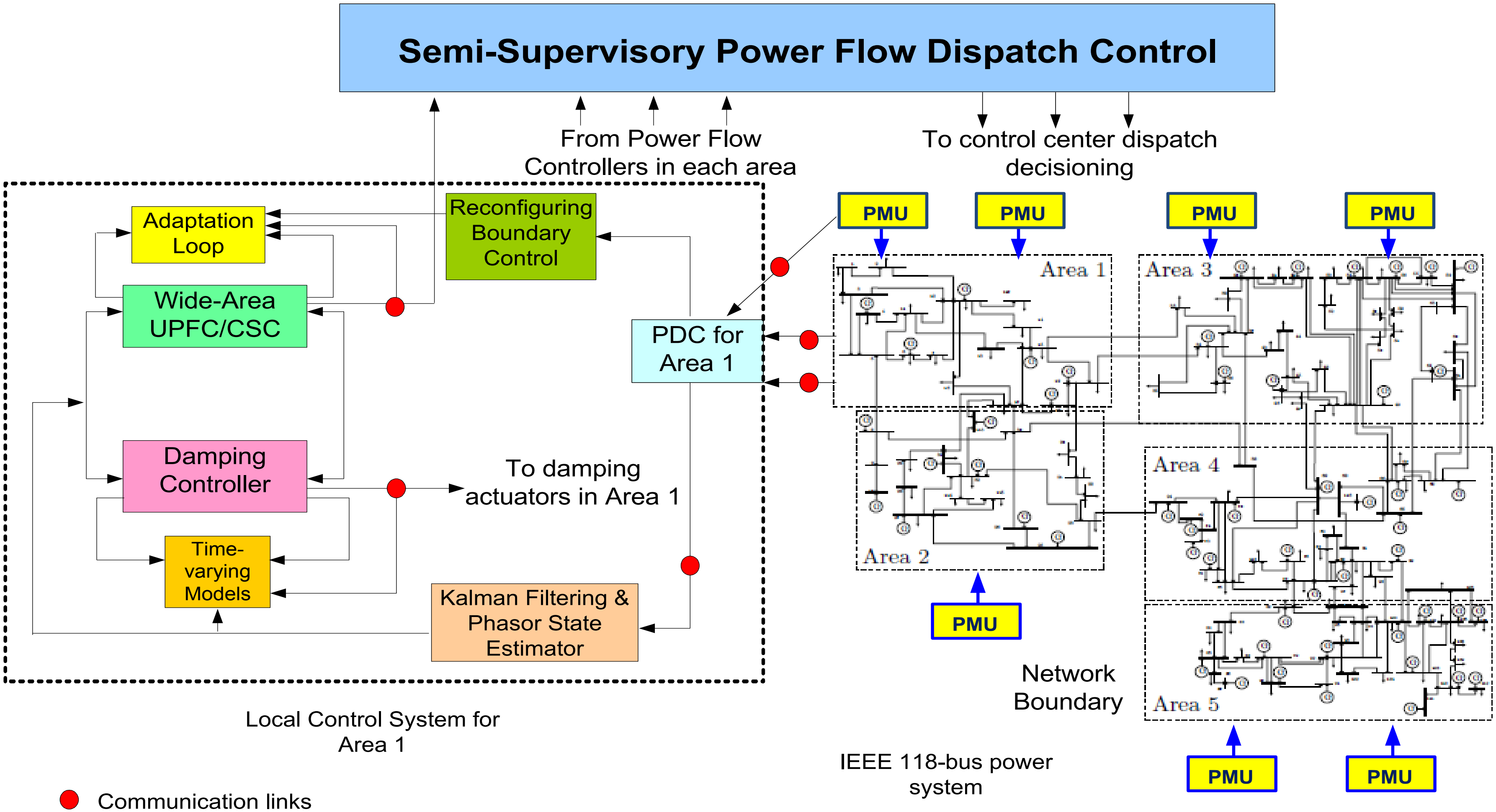
that minimizes *J*.



Architectures for Wide-Area Control

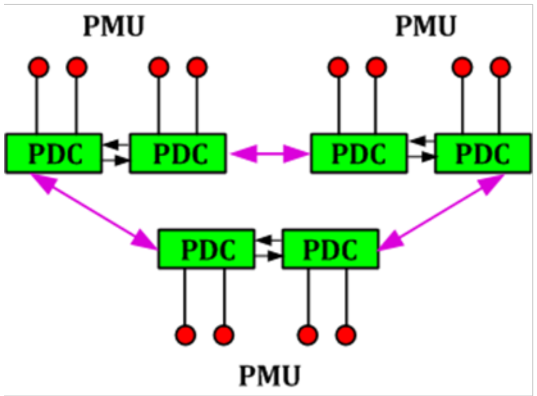
Scenario 2: Automatic or Semi-Automatic control

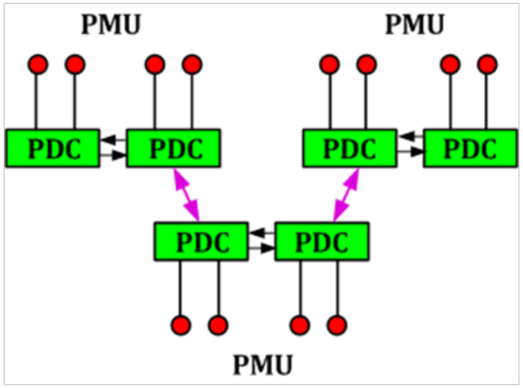
1. Supervisory: Power Flow Control using PMUs and FACTS

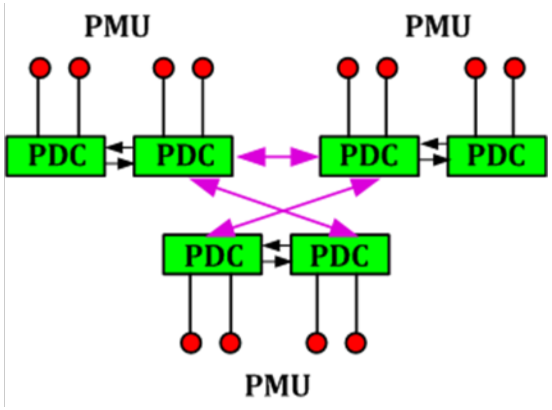


Architectures for Distributed Wide-Area Control

Distributed but local output-feedback:

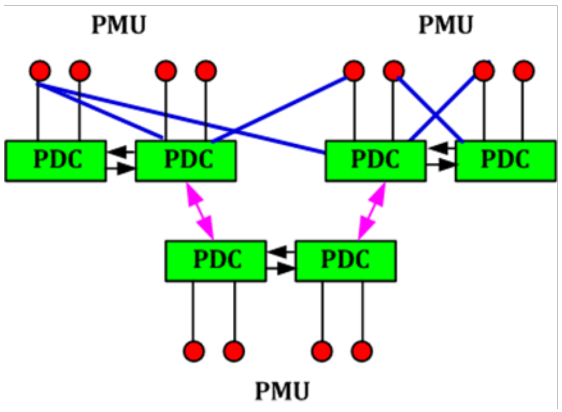


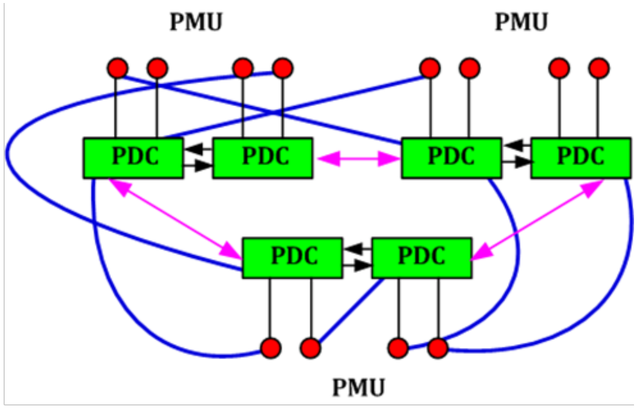




Examples: Privacy in data sharing beyond TSO, Voltage control

Distributed but remote output-feedback:





Examples: Inter-area oscillation damping, Power flow control, Disturbance rejection

Theoretical & Implementation Challenges

Theoretical challenges:

1. Can wide-area control be brought under a unifying theoretical framework?

H_∞, MPC, Cooperative Control, Adaptive learning control, Passivity-based control, Hybrid Systems

2. Will distributed control work in reality for such a complex system with so many different functionalities with so many different time-scales?

Implementation challenges:

1. Challenges in establishing a robust communication backbone -NASPINet
2. IEEE Standards, Privacy in data sharing agreements
3. Expensive infrastructure, must be on top of existing controls
4. Challenges in real-time computing, cloud computing and cyber-security
5. China & Sweden have implemented wide-area oscillation damping FACTS control

New Springer book on *Wide-Area Monitoring & Control* coming out later this year by Chakrabortty & Khargonekar

Conclusions

1. WAMS is a tremendously promising technology for control researchers
2. Control + Communications + Computing must merge
3. Plenty of new research problems – EE, Applied Math, Computer Science
4. Plenty of new control engineering problems
5. Right time to think mathematically – <u>Network theory</u> is imperative
6. Right time to pay attention to the bigger picture of the electric grid
7. Needs participation of young researchers!
8. Promises to create jobs and provide impetus to power engineering

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