ZJU-CSE Summer School

Distributed Load Frequency Control in Smart Grid

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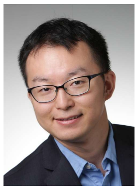
Shichao Liu



- Assistant Professor, DoE, Carleton
- IEEE Senior Member
- Associate Editor, *IEEE Access*
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- TC Member, IEEE IES Resilience and Security for Industrial Applications (ReSia)
- Keynote Speaker, Intl.Con.2MAE, 2017, May, Beijing, China
- Session Chairs, IEEE IES ISIE 2021

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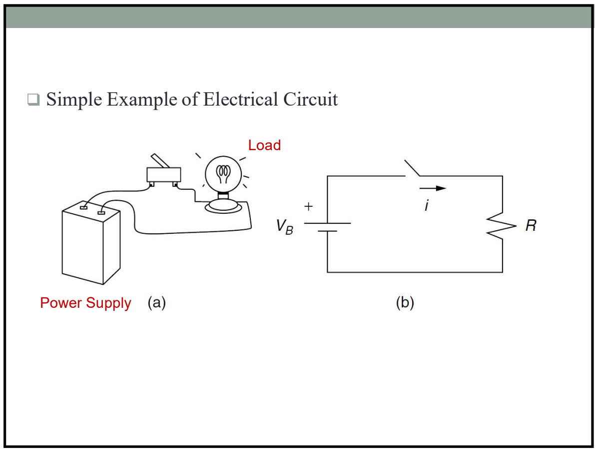
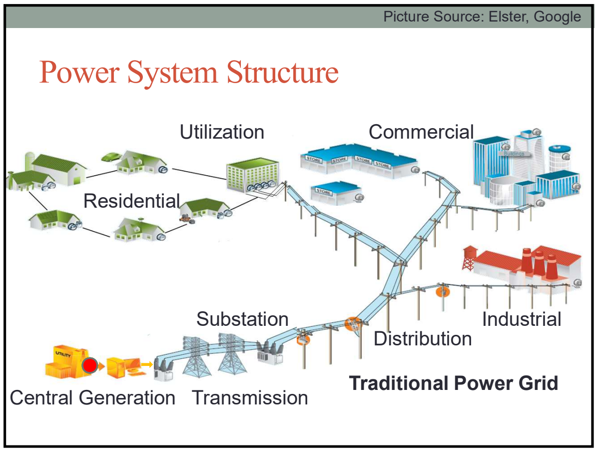
Outlines

- ❑ Introduction-Smart Grid
- ❑ Introduction-Load Frequency Control in Smart Grid
- ❑ Distributed Model-Based Load Frequency Control in Smart Grid
- ❑ Cyber Security in Secondary Frequency Control in Microgrids



- ❑ Simple Example of Electrical Circuit



Picture Source: Elster, Google

Power System Structure

Traditional Power Grid

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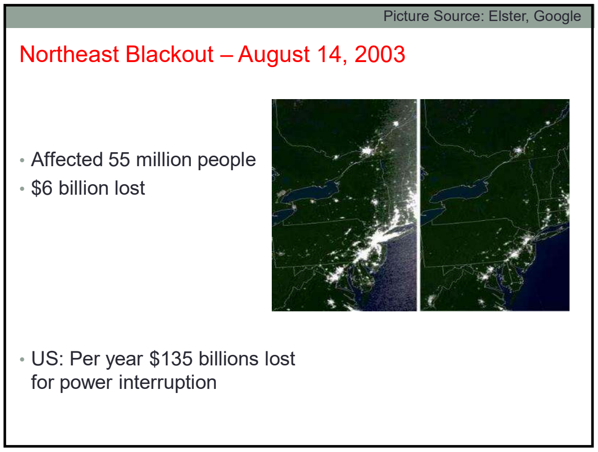
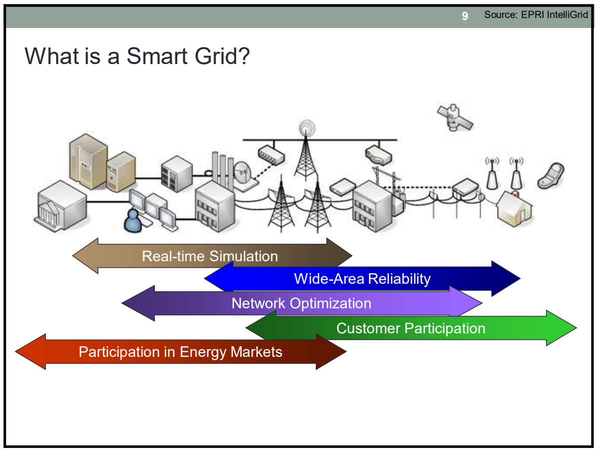


Picture Source: Elster, Google

Northeast Blackout – August 14, 2003

- Affected 55 million people
- $6 billion lost
- US: Per year $135 billions lost for power interruption

8



9 Source: EPRI IntelliGrid

What is a Smart Grid?

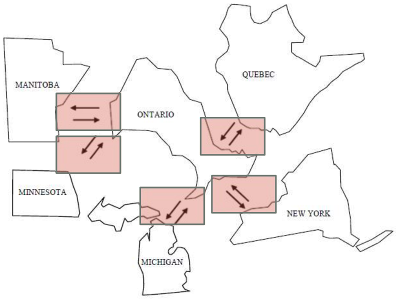
9

Comparisons

Traditional Power Grid	Smart Grid
Centralized Generation	Distributed Generation
Hierarchical	Networked
One-Way Communication	Two-Way Communication
Manual Restoration	Self-Healing
Few Customer Choices	Many Customer Choices
Limited Control	Pervasive Control

❑Multi-Area Power System

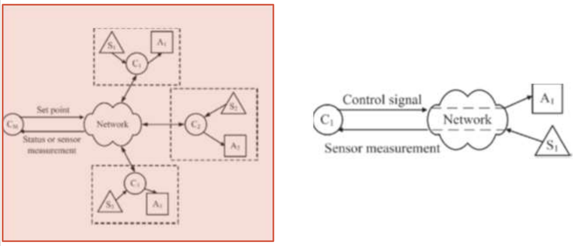
- ❑ Ontario Interconnection



Ontario Interconnection

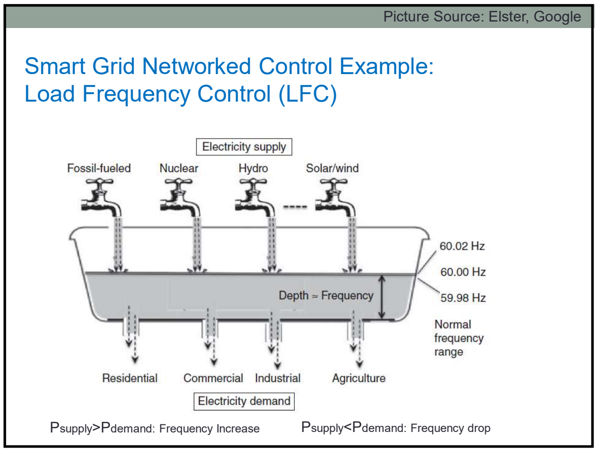
Networked Control System (NCS)

❑ Topologies



(a) Shared-network connection

(b) Data transfers of direct structure

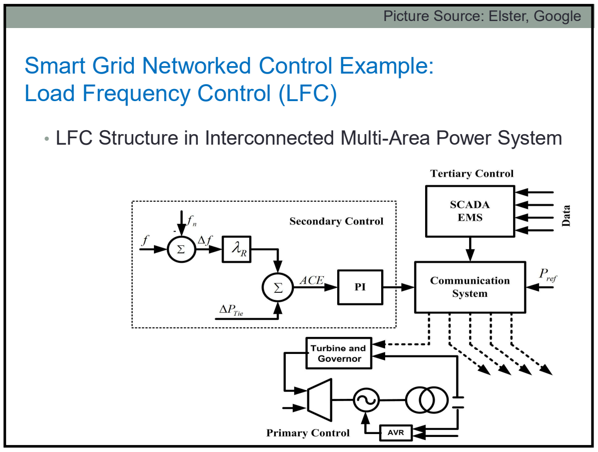


Picture Source: Elster, Google

Smart Grid Networked Control Example: Load Frequency Control (LFC)

$P_{supply}>P_{demand}$: Frequency Increase

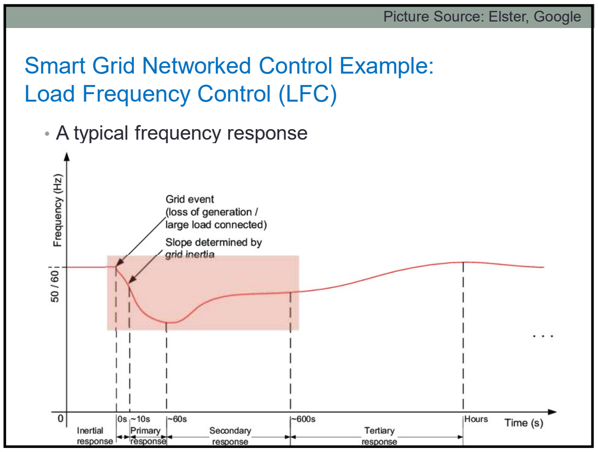
$P_{supply}<P_{demand}$: Frequency drop



Picture Source: Elster, Google

Smart Grid Networked Control Example: Load Frequency Control (LFC)

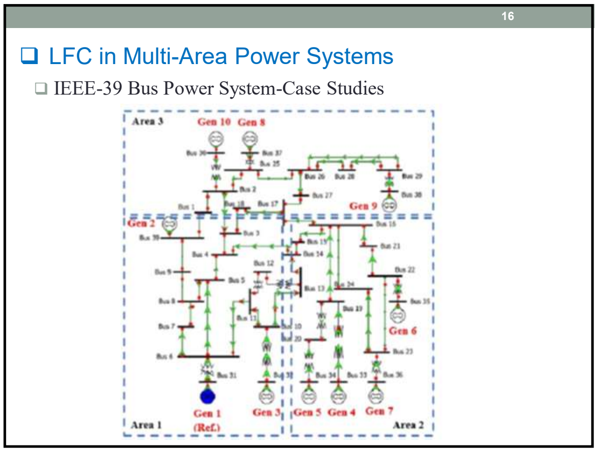
- LFC Structure in Interconnected Multi-Area Power System



Picture Source: Elster, Google

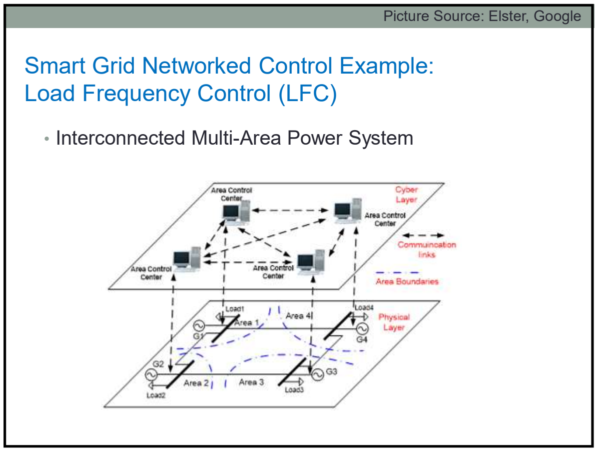
Smart Grid Networked Control Example: Load Frequency Control (LFC)

- A typical frequency response



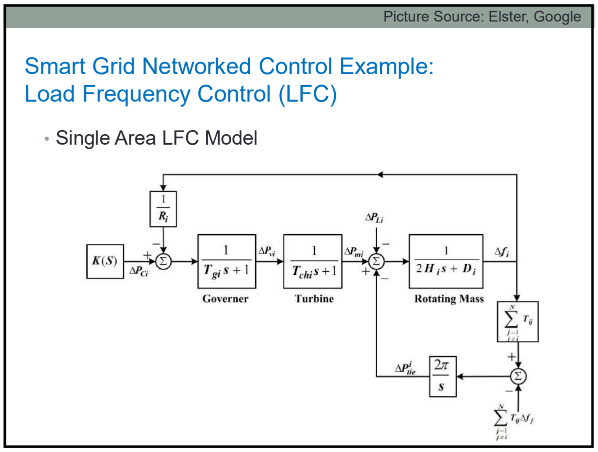
❑ LFC in Multi-Area Power Systems

- ❑ IEEE-39 Bus Power System-Case Studies


Picture Source: Elster, Google

Smart Grid Networked Control Example: Load Frequency Control (LFC)

- Interconnected Multi-Area Power System


Picture Source: Elster, Google

Smart Grid Networked Control Example: Load Frequency Control (LFC)

- Single Area LFC Model

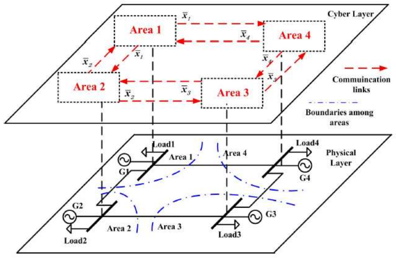
Picture Source: Elster, Google

Smart Grid Networked Control Example: Load Frequency Control (LFC)

- Challenges: Unreliable factors of communication links involved in LFC of Smart Grid
  - Communication Delays
  - Communication Failures
  - Limited Bandwidth
  - Cyber Attacks
- Questions need to be answered
  - How do these communication-related factors affect LFC of a smart grid?
  - How to compensate the performance degradation of a smart grid due to these communication-related factors?

Smart Grid Networked Control Example: Load Frequency Control (LFC)

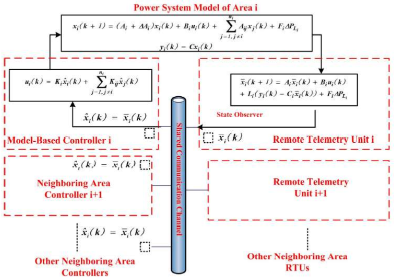
- Study 1: Limited Bandwidth



Four area power systems

Smart Grid Networked Control Example: Load Frequency Control (LFC)

- Study 1: Limited Bandwidth in Shared Communications



S. Liu et al., "Distributed Model-Based Control and Scheduling for LFC of Smart Grids Over Limited Bandwidth Networks," *IEEE Transactions on Industrial Informatics*, vol. 14, no. 5, pp. 1814-1823, May 2018

Smart Grid Networked Control Example: Distributed Load Frequency Control (LFC)

- Study 1: Limited Bandwidth in Shared Communications

The sampled discrete-time model for ith area with $i \in \{1, \cdots, n\}$ is:

$$\begin{cases} x_i(k+1) & = (A_i + \Delta A_i)x_i(k) + B_i u_i(k) \\ & + \sum\limits_{j=1, j\neq i}^{n} A_{ij} x_j(k) + F_i \Delta P_{L_i} \\ y_i(k) & = C_i x_i(k) \end{cases} \qquad (7)$$

where, $A_i = e^{A_i^c q}$, $A_{ij} = e^{A_{ij}^c q}$,$\Delta A_i = e^{\Delta A_i^c q}$ $B_i = \int_0^q e^{A_i^c \tau} B_i^c d\tau$, $C_i = C_i^c$, $F_i = \int_0^q e^{A_i^c \tau} F_i^c d\tau$ and q is the sampling period.

Smart Grid Networked Control Example: Distributed Load Frequency Control (LFC)

- Study 1: Limited Bandwidth in Shared Communications

In ith area, the following distributed model-based controller is designed

$$u_i(k) = K_i \hat{x}_i(k) + \sum_{j=1, j\neq i}^{n_i} K_{ij} \hat{x}_j(k), i \in \{1, 2, \cdots, n\} \quad (9)$$

$$\begin{cases} \hat{x}_i(k+1) = & A_i \hat{x}_i(k) + B_i u_i(k) \\ & + \sum\limits_{j=1, j\neq i}^{n_i} A_{ij} \hat{x}_j(k) + F_i \Delta P_{L_i}, k \neq t_k \\ \hat{x}_j(k+1) = & A_j \hat{x}_j(k) + B_j \hat{u}_j(k) \\ & + \sum\limits_{r=1, r\neq j}^{n_j} A_{jr} \hat{x}_r(k) + F_j \Delta P_{L_j}, k \neq t_k \\ \hat{u}_j(k) = & K_j \hat{x}_j(k) + \sum\limits_{j=1, r\neq j}^{n_j} K_{jr} \hat{x}_r(k) \\ \hat{x}_j(t_k) = & \bar{x}_j(t_k), j \in \{1, \cdots, n_i\}, k = t_k \end{cases} \qquad (10)$$

Smart Grid Networked Control Example: Distributed Load Frequency Control (LFC)

- Study 1: Limited Bandwidth in Shared Communications

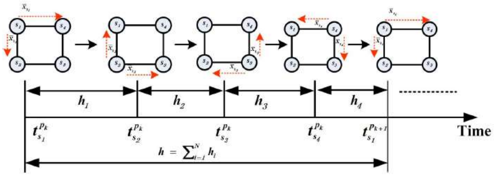
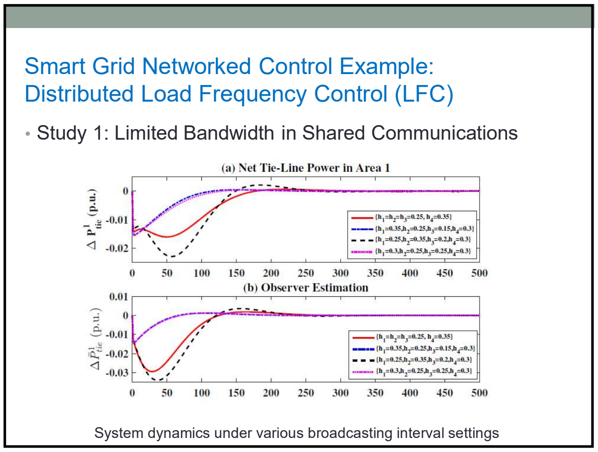


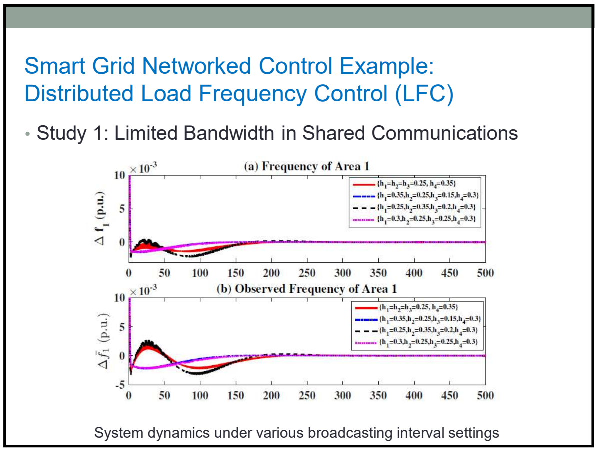
Illustration of the RTU broadcasting schedule



Smart Grid Networked Control Example: Distributed Load Frequency Control (LFC)

- Study 1: Limited Bandwidth in Shared Communications

System dynamics under various broadcasting interval settings



Smart Grid Networked Control Example: Distributed Load Frequency Control (LFC)

- Study 1: Limited Bandwidth in Shared Communications

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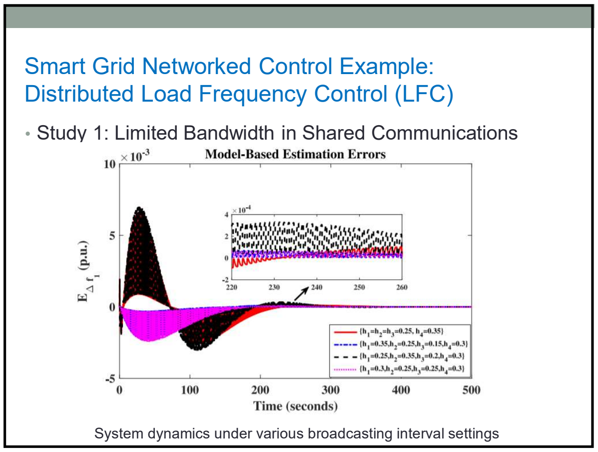
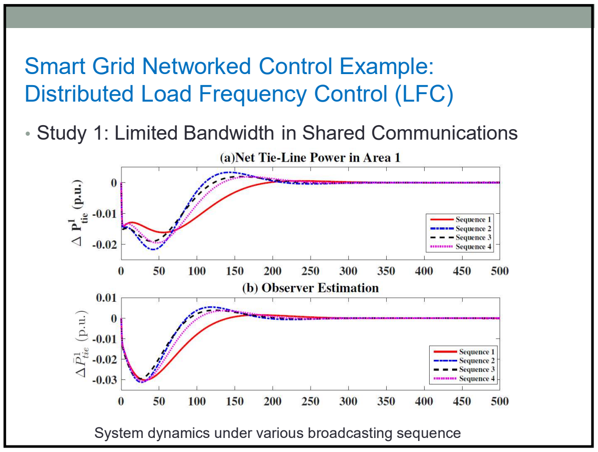


Smart Grid Networked Control Example: Distributed Load Frequency Control (LFC)

- Study 1: Limited Bandwidth in Shared Communications

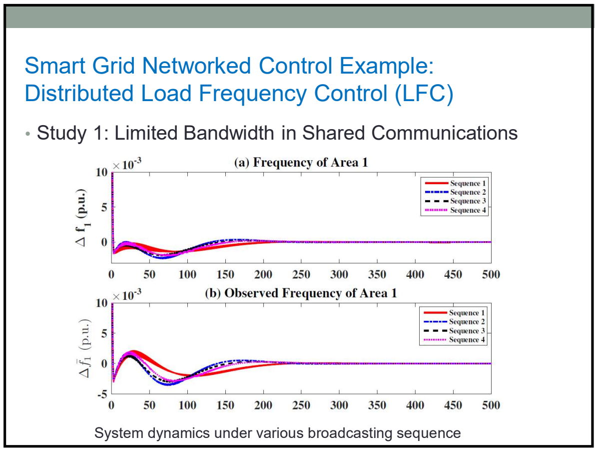
System dynamics under various broadcasting interval settings



Smart Grid Networked Control Example: Distributed Load Frequency Control (LFC)

- Study 1: Limited Bandwidth in Shared Communications

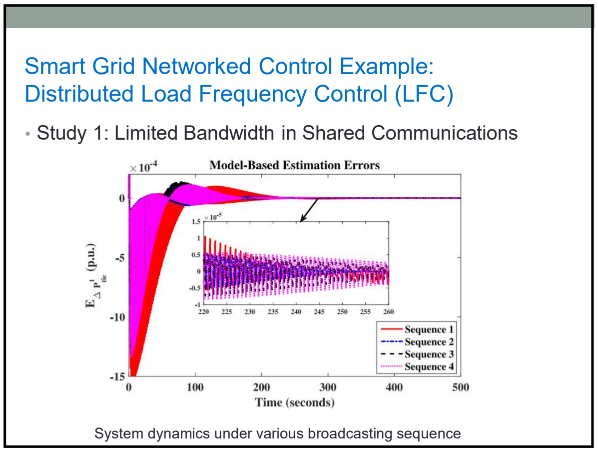
System dynamics under various broadcasting sequence



Smart Grid Networked Control Example: Distributed Load Frequency Control (LFC)

- Study 1: Limited Bandwidth in Shared Communications

System dynamics under various broadcasting sequence



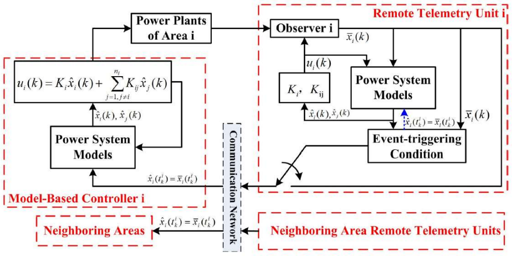
Smart Grid Networked Control Example: Distributed Load Frequency Control (LFC)

- Study 1: Limited Bandwidth in Shared Communications

System dynamics under various broadcasting sequence

Smart Grid Networked Control Example: Distributed Load Frequency Control (LFC)

- Study 2: Limited Bandwidth in Shared Communications



[Ref] S. Liu, W. Luo and L. Wu, "Co-Design of Distributed Model-Based Control and Event-Triggering Scheme for Load Frequency Regulation in Smart Grids," in IEEE Transactions on Systems, Man, and Cybernetics: Systems, vol. 50, no. 9, pp. 3311-3319, Sept. 2020

Smart Grid Networked Control Example: Distributed Load Frequency Control (LFC)

- Study 2: Limited Bandwidth in Shared Communications

Event-Triggering Condition

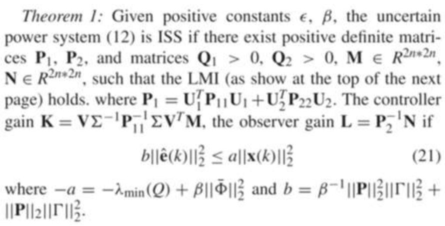
$$b||\hat{\mathbf{e}}_i(k)||_2^2 \leq a||\mathbf{x}_i(k)||_2^2$$

where $\hat{\mathbf{e}}_i(k) = \bar{\mathbf{x}}_i(k) - \hat{\mathbf{x}}_i(k)$ denotes the prediction error between the state observation $\bar{\mathbf{x}}_i(k)$ and $\hat{\mathbf{x}}_i(k)$ which is the state estimated based on the power system model in the RTU, and a and b are are scalars to be designed in terms of the event-triggering mechanism.

Smart Grid Networked Control Example: Distributed Load Frequency Control (LFC)

- Study 2: Limited Bandwidth in Shared Communications

Event-Triggering Condition: $b||\hat{\mathbf{e}}_i(k)||_2^2 \leq a||\mathbf{x}_i(k)||_2^2$



Theorem 1: Given positive constants ϵ, β, the uncertain power system (12) is ISS if there exist positive definite matrices $\mathbf{P}_1$, $\mathbf{P}_2$, and matrices $\mathbf{Q}_1 > 0$, $\mathbf{Q}_2 > 0$, $\mathbf{M} \in R^{2n*2n}$, $\mathbf{N} \in R^{2n*2n}$, such that the LMI (as show at the top of the next page) holds. where $\mathbf{P}_1 = \mathbf{U}_1^T\mathbf{P}_{11}\mathbf{U}_1 + \mathbf{U}_2^T\mathbf{P}_{22}\mathbf{U}_2$. The controller gain $\mathbf{K} = \mathbf{V}\Sigma^{-1}\mathbf{P}_{11}^{-1}\Sigma\mathbf{V}^T\mathbf{M}$, the observer gain $\mathbf{L} = \mathbf{P}_2^{-1}\mathbf{N}$ if

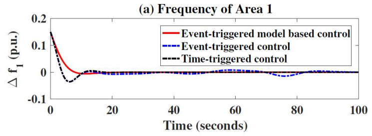
$$b||\hat{\mathbf{e}}(k)||_2^2 \leq a||\mathbf{x}(k)||_2^2 \qquad (21)$$

where $-a = -\lambda_{\min}(Q) + \beta||\bar{\Phi}||_2^2$ and $b = \beta^{-1}||\mathbf{P}||_2^2||\Gamma||_2^2 + ||\mathbf{P}||_2||\Gamma||_2^2$.

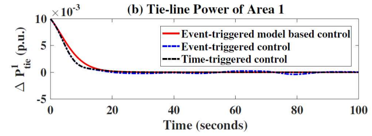
Smart Grid Networked Control Example: Distributed Load Frequency Control (LFC)

- Study 2: Limited Bandwidth in Shared Communications

(a) Frequency of Area 1



(b) Tie-line Power of Area 1

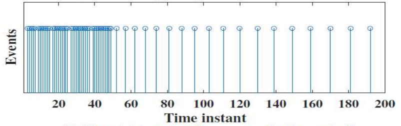


Even-triggering performance

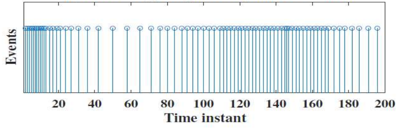
Smart Grid Networked Control Example: Distributed Load Frequency Control (LFC)

- Study 2: Limited Bandwidth in Shared Communications

(a) Event-triggering model-based control



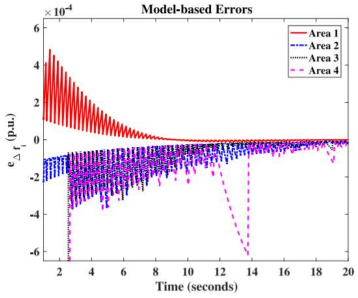
(b) Event-triggering linear quadratic control



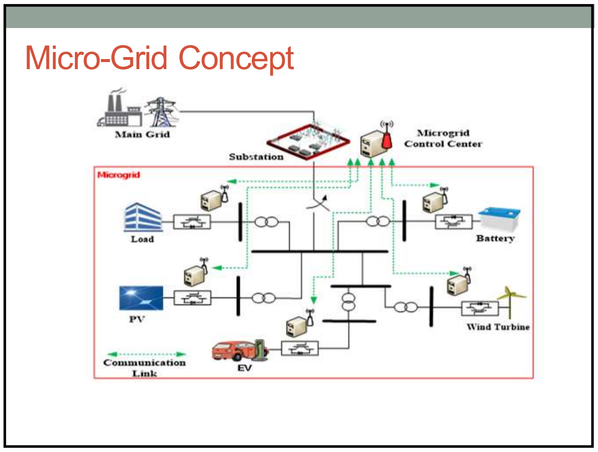
Even-triggering performance

Smart Grid Networked Control Example: Distributed Load Frequency Control (LFC)

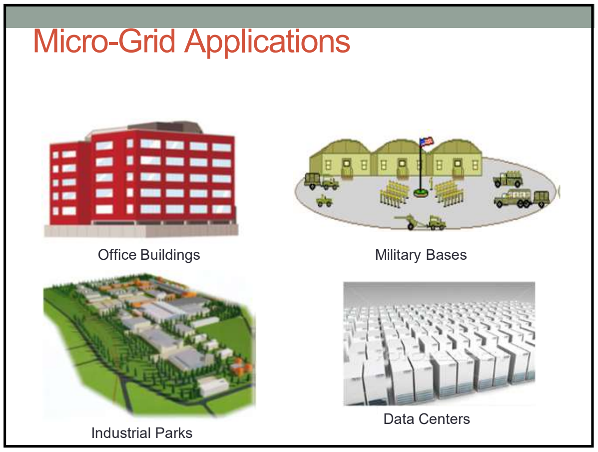
- Study 2: Limited Bandwidth in Shared Communications



Model-based Errors



Micro-Grid Concept



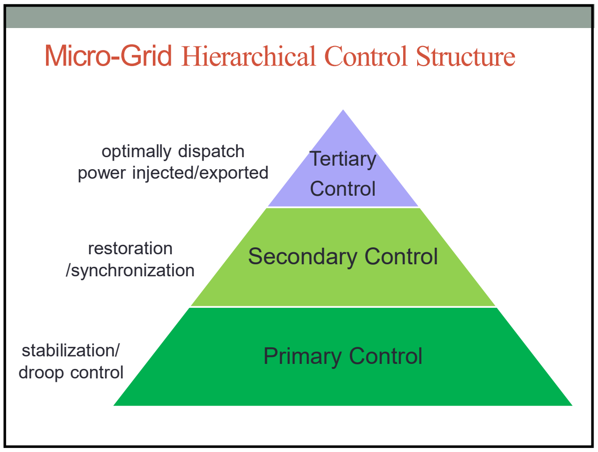
Micro-Grid Applications

Office Buildings

Military Bases

Industrial Parks

Data Centers



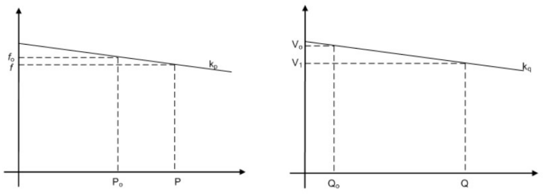
Micro-Grid Hierarchical Control Structure

optimally dispatch power injected/exported — Tertiary Control

restoration /synchronization — Secondary Control

stabilization/ droop control — Primary Control

Micro-Grid Droop Control



$$f = f_0 - k_p(P - P_0)$$ $$V_1 = V_0 - k_v(Q - Q_0)$$

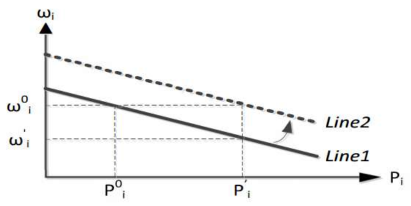
An experimental study of frequency droop control in a low-inertia microgrid, Andrew Bollman

Resynchronization of Islanded Microgrid

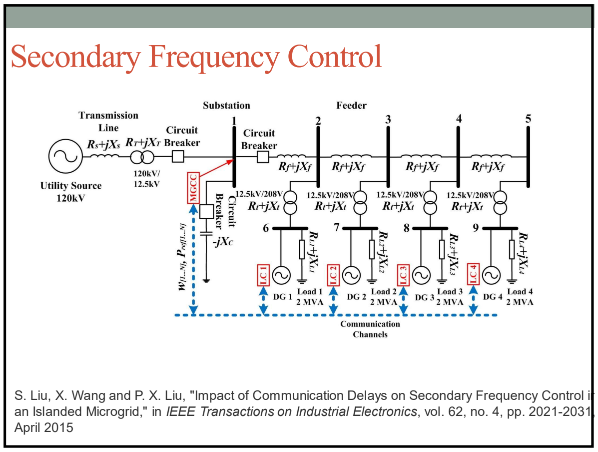
- Function of a resynchronization controller
  - Ensure smooth reconnection of microgrid and main grid
  - Restore the nominal frequency
  - Two kinds of control strategies
    - ---Centralized controller
    - ---Distributed controller

Secondary Frequency Control

- Basic Principle

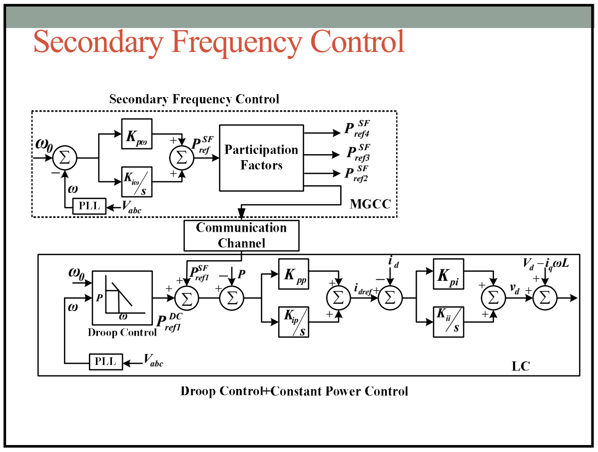


secondary frequency control, Alireza Raghami

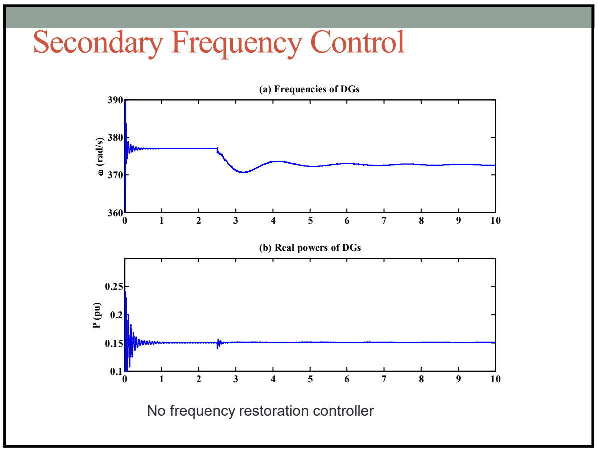


Secondary Frequency Control

S. Liu, X. Wang and P. X. Liu, "Impact of Communication Delays on Secondary Frequency Control i an Islanded Microgrid," in *IEEE Transactions on Industrial Electronics*, vol. 62, no. 4, pp. 2021-2031 April 2015

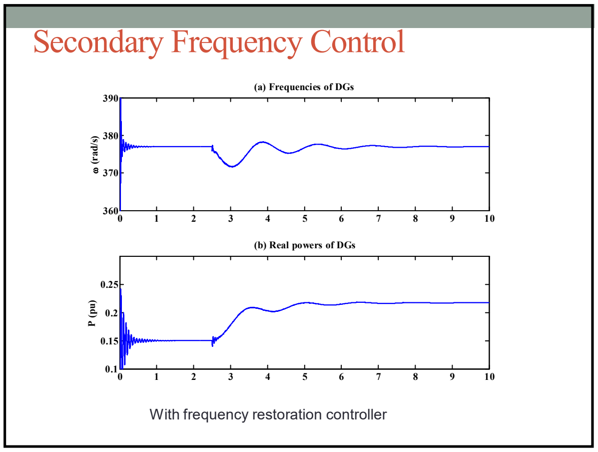


Secondary Frequency Control



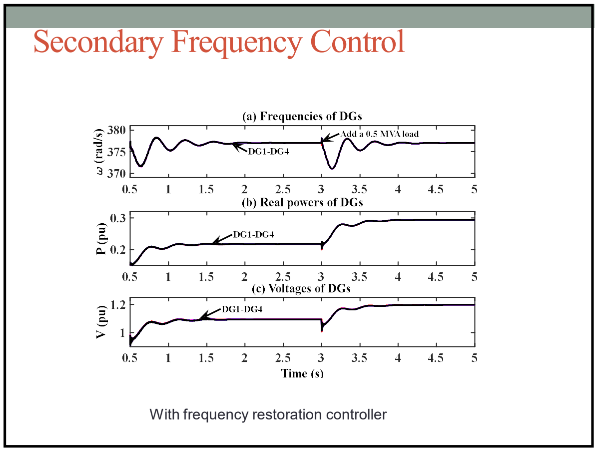
Secondary Frequency Control

No frequency restoration controller



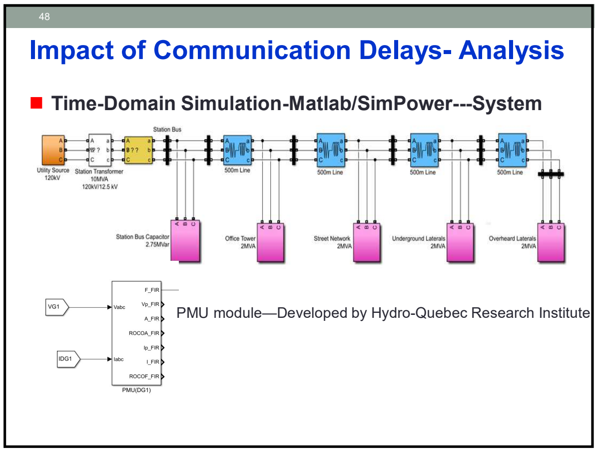
Secondary Frequency Control

With frequency restoration controller



Secondary Frequency Control

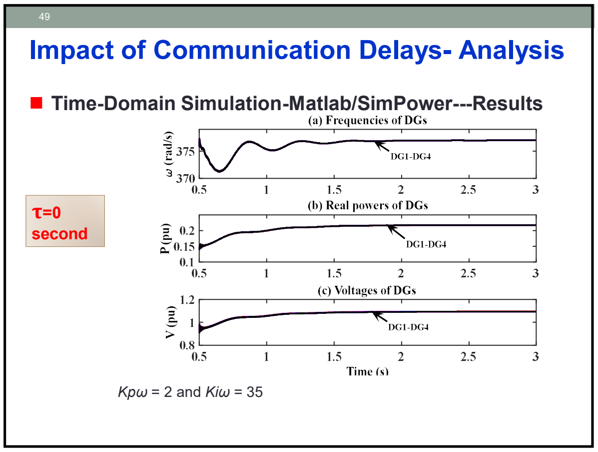
With frequency restoration controller



Impact of Communication Delays- Analysis

- Time-Domain Simulation-Matlab/SimPower---System

PMU module—Developed by Hydro-Quebec Research Institute

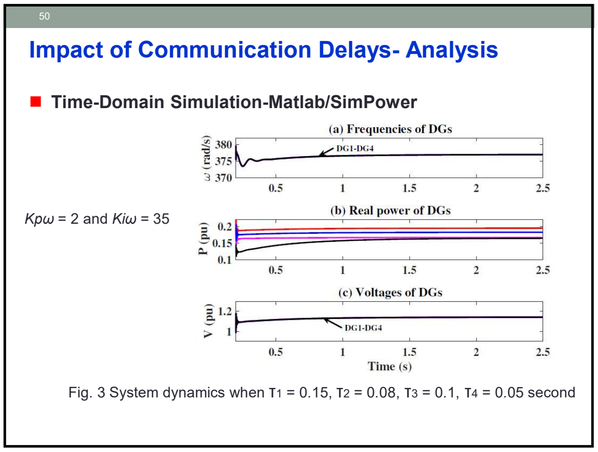


Impact of Communication Delays- Analysis

- **Time-Domain Simulation-Matlab/SimPower---Results**

τ=0 second

Kpω = 2 and *Kiω* = 35

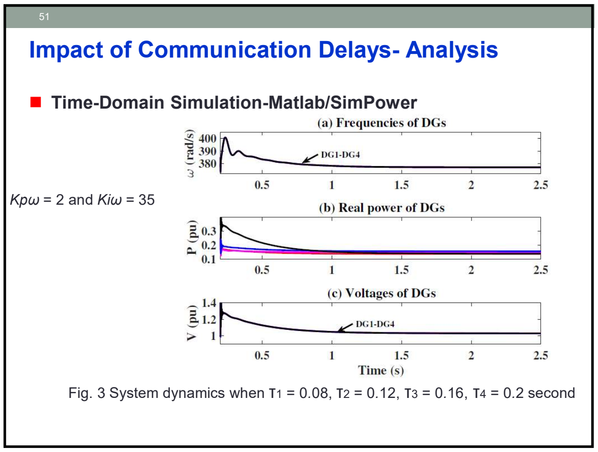


Impact of Communication Delays- Analysis

- **Time-Domain Simulation-Matlab/SimPower**

Kpω = 2 and *Kiω* = 35

Fig. 3 System dynamics when $\tau_1 = 0.15$, $\tau_2 = 0.08$, $\tau_3 = 0.1$, $\tau_4 = 0.05$ second

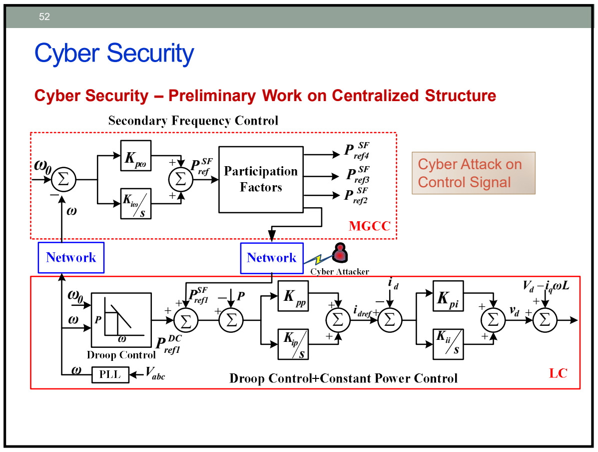


Impact of Communication Delays- Analysis

- **Time-Domain Simulation-Matlab/SimPower**

Kpω = 2 and *Kiω* = 35

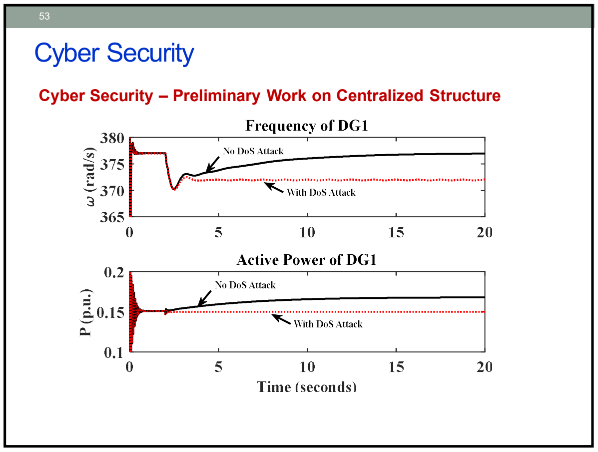
Fig. 3 System dynamics when $\tau_1 = 0.08$, $\tau_2 = 0.12$, $\tau_3 = 0.16$, $\tau_4 = 0.2$ second



Cyber Security

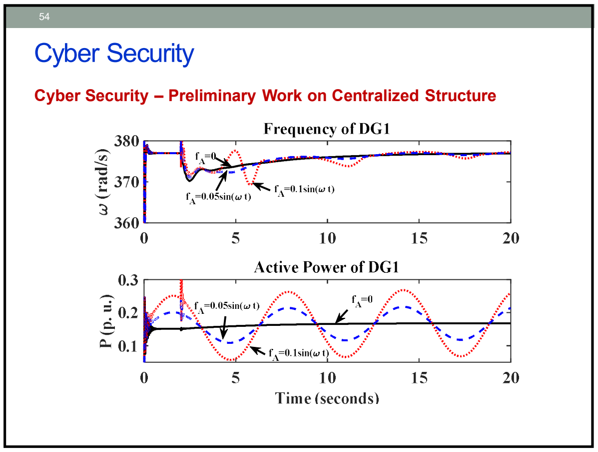
Cyber Security – Preliminary Work on Centralized Structure

Cyber Attack on Control Signal



Cyber Security

Cyber Security – Preliminary Work on Centralized Structure



Cyber Security

Cyber Security – Preliminary Work on Centralized Structure

Towards A Smarter and Stronger Grid

Thank You!