Carnegie Mellon

Electric Energy Systems Group

Electrical & Computer ENGINEERING

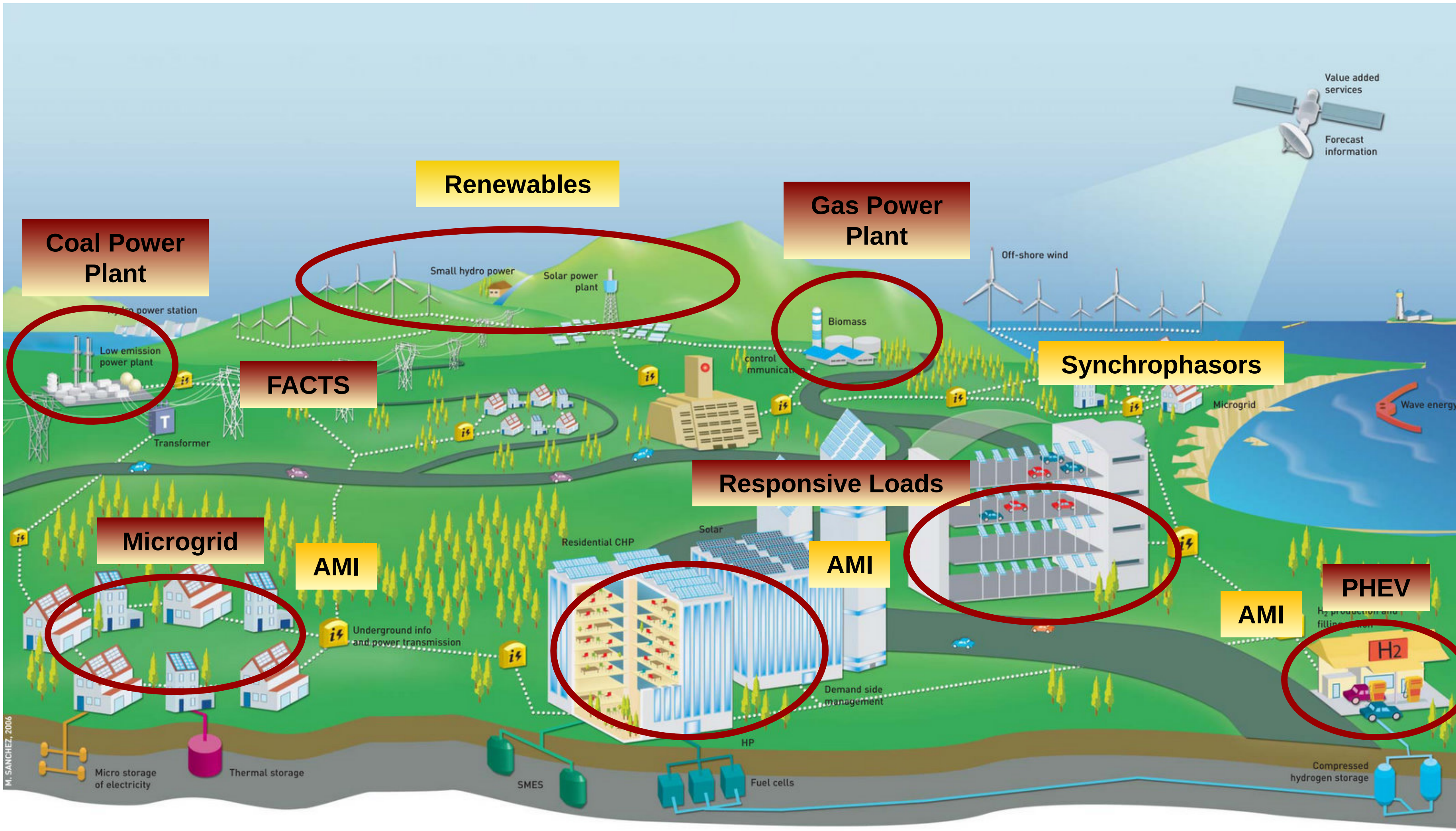
TENTH CARNEGIE MELLON CONFERENCE ON THE ELECTRICITY INDUSTRY

PRE-CONFERENCE WORKSHOP

Enhanced AGC (E-AGC) for Quality of Response (QoR) Control in Dynamic Electric Power System

Presenter: Xia Miao

Many DERs can participate in frequency stabilization and regulation



AMI: Advanced Metering Infrastructure PHEV: Plug-in Hybrid Electric Vehicle FACTS: Flexible AC Transmission System

[Figure from: http://ec.europa.eu/energy/gas_electricity/smartgrids/smartgrids_en.htm]

The Changing Electric Power System Dynamics

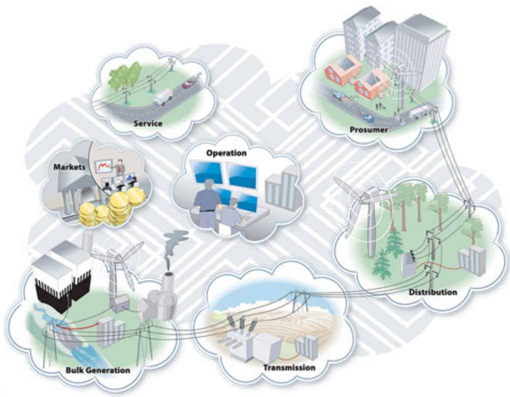
- Changes and challenges brought about by the deployment of new technologies to the control of electric power systems dynamics
  - Change 1: new devices & components generally change the characteristics of a power grid
    - FACTS devices increase maximum power transfer on specific lines of interest by reducing the line impedance; this, in turn, leads to stronger interactions between different power plants
  - Challenge 1: today's primary stabilization controllers (governors, excitation systems) are tuned locally by modeling the external system as a static Thevenin equivalent. Dynamics not captured, instability caused by unmodeled dynamics (i.e. interactions) ignored [1].
  - Change 2: fast-varying persistent disturbances injected by the renewable energy sources
  - Challenge 2: State-of-the-art hierarchical control assumes temporal separation of disturbances into fast continuous and slow quasi-stationary and designs control separately; this assumption no longer holds, therefore, temporal separation of control is no longer justified.

[1] X. Miao, K.D. Bachovchin, M. D. Ilic . Effect of load type and un-modeled dynamics in load on the equilibria and stability of electric power system. Submitted to CDC 2015

Potential of Making the System "Green" by Using Smarts

- Opportunity: coordination for control of power system dynamics
- Opportunity: better control performance enabled by advanced sensing and communication technologies
- Toward better performance:
  - coordination for control needs to be practically implementable
  - What is the right information for communication ?

- Our point of view: Understand the physical characteristics of large-scale electric power system.



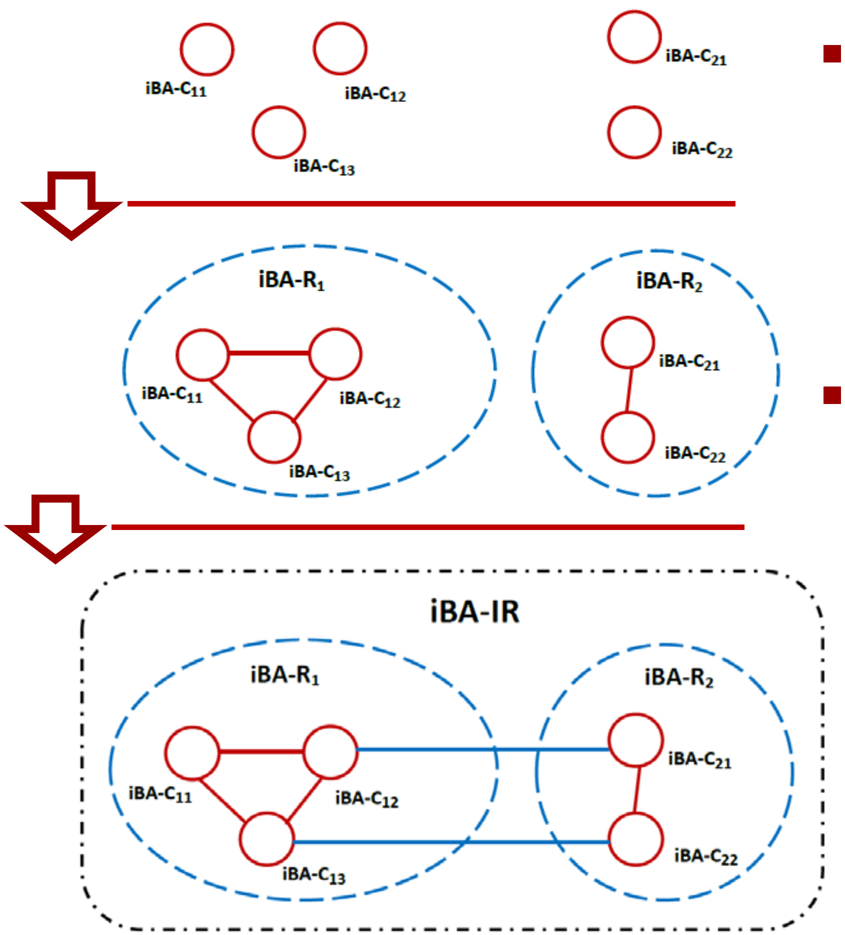
"Green" components
"Grey" system…

E-AGC—Example of DyMonDS-based frequnecy control

- Background & Motivation
- Foundation of Enhanced AGC (E-AGC) Approach
  - Structure-Preserving Modeling Method
  - Inter-area Variable (IntV)
- Model-Based Design of the E-AGC Approach
  - Interaction-Based Quality of Response (QoR) Analysis
  - Model-Based E-AGC
- Implementation in SGRS
- Numerical Simulations

Fundamental Concept: Structure-Preserving Modeling

- A concept of **Intelligent Balancing Authority (iBA)** in earlier work [2]



From iBA-C to iBA-R and iBA-IR layers (bottom-up approach)

- Three-Layered iBAs
  - ✓ **iBA-C:** component layer
  - ✓ **iBA-R:** region layer
  - ✓ **iBA-IR**: Inter-region layer

- General modeling framework
  - ✓ **iBA-C**
    - Local dynamics of the component
    - External interactions with other components
  - ✓ **iBA-R**
    - All the variables of iBA-Cs combined in each iBA-R
  - ✓ **iBA-IR**
    - All the variables of iBA-Rs combined in iBA-IR

[2] M.D. Ilic and Qixing Liu. Toward standards for model-based control of dynamic interactions in large electric power grids. In Signal Information Processing Association Annual Summit and Conference (APSIPA ASC) 2012, pages 1–8, 2012.

Fundamental Concept: Structure-Preserving Modeling

- Structural representation of multiple administrative layers in 5 Bus System
  - Structure is preserved

❖ iBA-C: component layer model

$$\dot{x}_{c,i} = A_{c,i}x_{c,i} + B_{c,i}u_{c,i} + \sum_{i=1}^{N_c^{ir}} A_{c,ij}x_{c,j} + H_{c,i}P_{d,i},$$
$$x_{c,i}(t_0) = x_{ci0},$$

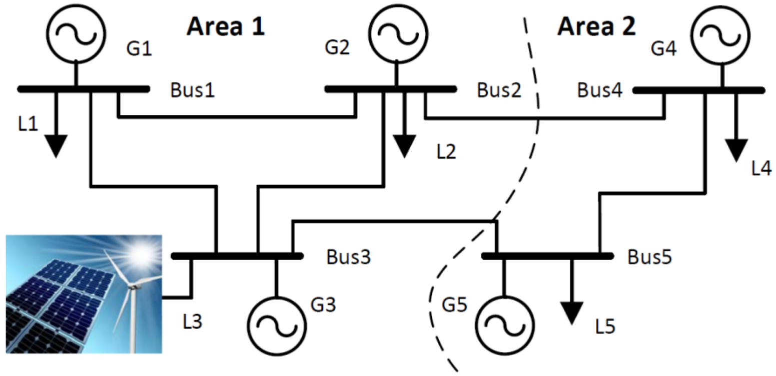
Structure Preserving

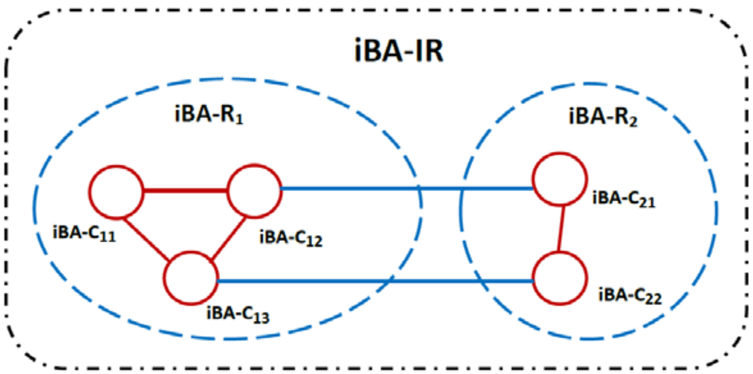
❖ iBA-R: region layer model

$$\dot{x}_{r,k} = A_{r,k}x_{r,k} + B_{r,k}u_{r,k} + \sum_{h=1}^{N_r} A_{r,kh}x_{r,h} + H_{r,k}P_{r,k}^{d},$$
$$x_{r,k}(t_0) = 0,$$

❖ iBA-IR: Inter-region layer model

$$\dot{x}_{ir} = A_{ir}x_{ir} + B_{ir}u_{ir} + H_{ir}d_{ir}^{L}, \quad x_{ir}(t_0) = 0,$$





A System Representation with Three iBA Layers

Fundamental Concept: Inter-area Variable (IntV)

- The notion of IntV was originally proposed in [3] to capture an effect driven only by inter-area dynamics.
- New Definition [4]:

Given a dynamic component (subsystem), its IntV Z is an output variable in terms of the local states of the component (subsystem) and it satisfies:

$$Z \equiv constant$$

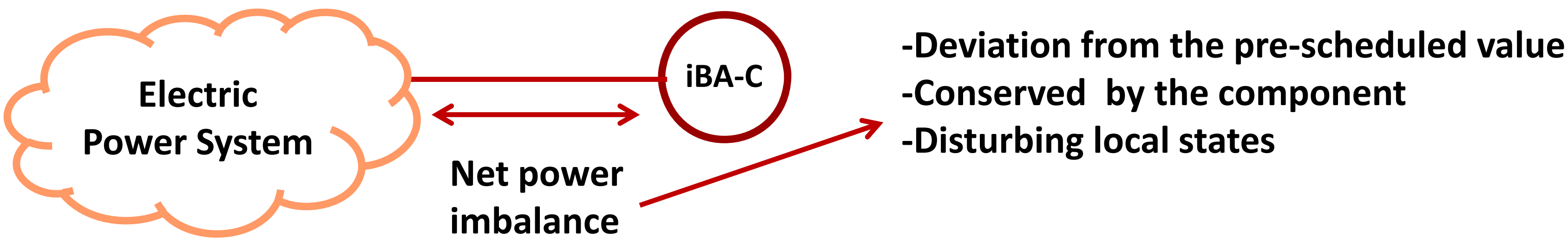
when the component (subsystem) is free of any conserved net power imbalance

- No steady state assumption
- A time-varying response of Z indicates the existence of a non-zero conserved net power imbalance that may further lead to unacceptable QoR of system dynamics

[3] M. D. Ilic and J. Zaborszky, Dynamics and Control of Large Electric Power Systems. New York: Wiley Interscience, 2000
[4] Q. Liu. Wide-Area Coordination for Frequency Control in Complex Power Systems. Ph.D. Thesis, Carnegie Mellon University, Aug 2013.

Interaction-Based Quality of Response Analysis

- Stabilized systems concerned
- To exploit the effects of interactions on frequency QoR
- Problematic QoR fundamentally caused by conserved net power imbalance



- **Model-based illustration:** $\dot{x}_{c,i} = A_{c,i}x_{c,i} + B_{c,i}u_{c,i} - F^{G}_{c,i}P_{G,i}, \quad x_{c,i}(t_0) = x_{ci0},$
- **Aggregated interaction with the external system**

From Physics to Mathematics

- Mathematical model of the conserved net power imbalance
  - Reflected by the rank deficiency of $A_{c,i}$

$$\dot{x}_{c,i} = A_{c,i}x_{c,i} + B_{c,i}u_{c,i} - F_{c,i}^{G}P_{G,i},$$
$$x_{c,i}(t_0) = x_{ci0},$$

  - In the 4-th order G-T-G model, $\mathrm{rank}(A_{c,i}) = 3$

Disturbance on P_G conserved by the zero eigenmode

⇩

Conservation of power

  - Interaction variable (IntV) [Ilic, 5] applied to represent the dynamics

$$z_{c,i} = T_{c,i}x_{c,i}, \quad \text{where} \quad T_{c,i}A_{c,i} = 0, \quad T_{c,i} \text{ unique (up to a scalar)}$$

$$\dot{z}_{c,i} = -P_{G,i}, \ \text{when } u_{c,i} = 0$$

Net power imbalance in terms of local states

[5] M. D. Ilic and X.S. Liu. A simple structural approach to modeling and analysis of the inter-area dynamics of the large electric power systems: Part I–linearized models of frequency dynamics. In Proceedings of the 1993 North American Power Symposium, pages 560–569, Washington, DC, October 1993.

Interaction-Based Quality of Response Analysis

- The notion of IntV used for QoR analysis
  - Component-level

$$\dot{x}_{c,i} = A_{c,i} x_{c,i} + F_{c,i}^{G} \dot{z}_{c,i}, \;\; x_{c,i}(t_0) = x_{ci0},$$

Proved [Liu,4]: $\text{when } \dot{z}_{c,i} = 0, \;\; x_{ci0} = 0, \;\; \Rightarrow \;\; x_{c,i} = 0$

  - System-level

$$\text{when all } \dot{z}_{c,i} = 0, \;\; x_{ci0} = 0, \;\; \Rightarrow \;\; \text{ensured QoR for each iBA-C}$$

  - QoR: monitoring via investigating the time variation of IntVs

[4] Q. Liu. Wide-Area Coordination for Frequency Control in Complex Power Systems. Ph.D. Thesis, Carnegie Mellon University, Aug 2013.

Control objective of E-AGC

- Objective: cost-effectiveness
  - Acceptable frequency QoR of the closed-loop system
  - Avoidance of utilizing high-cost control resources
- Control criteria:
  - To maintain the IntVs of all iBA-Cs at constant
  - To reduce system-wide control cost by using coordination

Design of the E-AGC

- System-level LQR-based output-feedback control design

IntVs of all iBA-Cs in the system: $z_s^C = \left[z_{c,1}, z_{c,2}, \ldots, z_{c,N_c^{ir}}\right]^T.$

$$\min_{u_{ir}} \quad J = \frac{1}{2}\int_{t_0}^{\infty} \left[(z_s^C)^T Q_{ir}^z z_s^C + (u_{ir})^T R_{ir}^z u_{ir}\right] d\tau,$$

$$\text{s.t.} \quad \dot{x}_{ir} = A_{ir}x_{ir} + B_{ir}u_{ir}, \; x_{ir}(t_0) = x_{ir0}.$$

Resulting centralized control law for each component: $u_{c,i}^{eagc} = -\sum_{i=1}^{N_c^{ir}} k_{c,ij} z_{c,j}.$ $\quad u_{ir}^{eagc} = \begin{bmatrix} u_{c,1}^{eagc} \\ \vdots \\ u_{N_c^{ir}}^{eagc} \end{bmatrix}$

IntVs used as the information for control coordination

Control input signals to the speed governor comprise of the signals of the proposed stabilization control and the E-AGC

$$u_{c,i} = u_{c,i}^{loc} + u_{c,i}^{eagc}$$

Dynamic E-AGC –Generalization of today's Steady State AGC

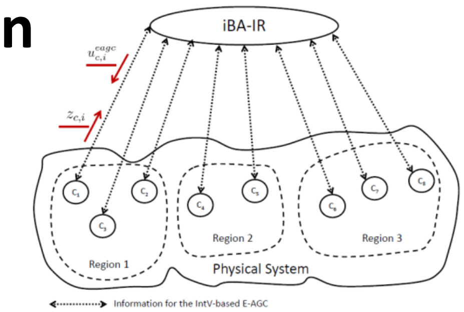
- **Widely used frequency QoR control: Automatic Generation Control (AGC)**
- **Control objective: decentralized at each control area, causing high system-level control cost**
  - Acceptable frequency QoR of the closed-loop system
  - Efficient utilization of control resources at the control-area level
- **Control criteria: steady state-based**
  - To maintain the ACE of each control area at zero via PID control

$$ACE = (P_{tie} - P_{tie}^{ref}) + 10\beta_A(f_A - f_A^{ref}), \text{ where } f_A = \frac{\omega_A}{2\pi}$$

A control area

  - To coordinate control resources according to pre-specified participation factors
- **E-AGC provides system-level coordination of controllers contributing to QoR**
  - IntV (dynamic IEE) used as the feedback signal
  - Dynamic model used for control design
  - LQR-based design technique used for achieving system-level coordination

Implementation in SGRS: Module Definition



Generalized Module Mapping Table:

Component Name	iBA-C(Gen)	iBA-C(Load)	iBA-C(Dist)	iBA-IR
Module Type	EAGC_Gen	EAGC_L/Dist	EAGC_Dist	EAGC

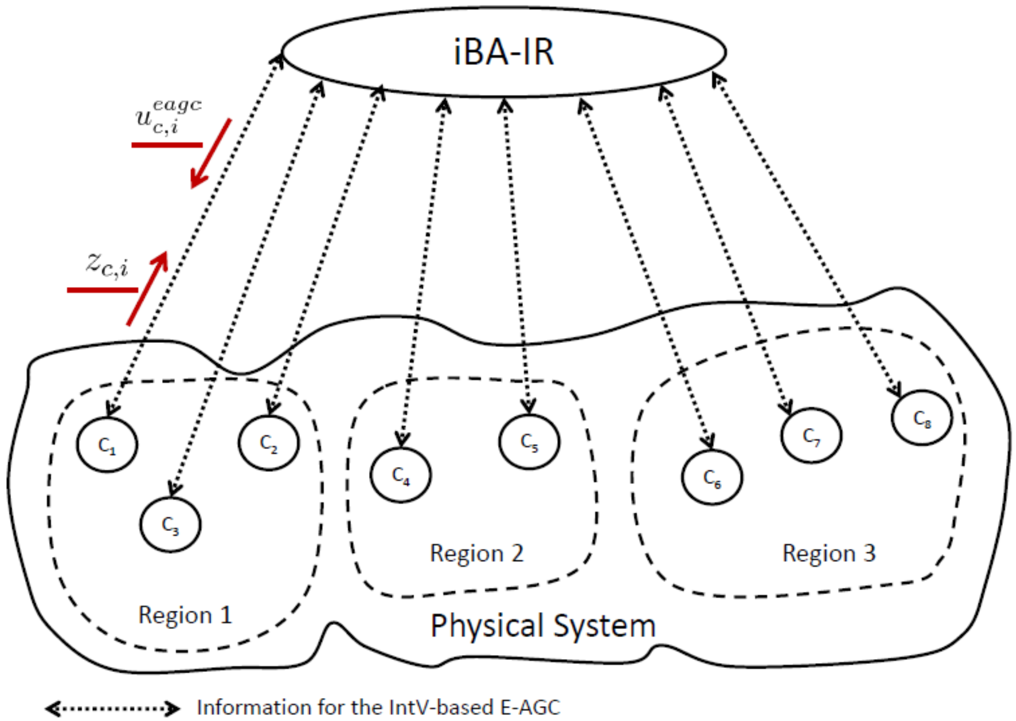
Generalized Module Class Definition Table:

Module Type	iBA-C(Gen/Load/Dist)	iBA-IR

Module Methods	▪ IntV *Z* measurement
	▪ Comm.from EAGC (read())
	  ▪ Get u^{eagc}
	▪ Comm.to EAGC (write())
	  ▪ Send IntV *Z*
	▪ Run function (while loop)
		▪ Calculater
		  ▪ Compute control signal u^{eagc}
		▪ Comm.to iBA-C
		  ▪ Send u^{eagc}
		▪ Comm.from EAGC (write())
		  ▪ Get IntV *Z*
		▪ Run function (while loop)

EESG

Implementation in SGRS: Communication Infrastructure



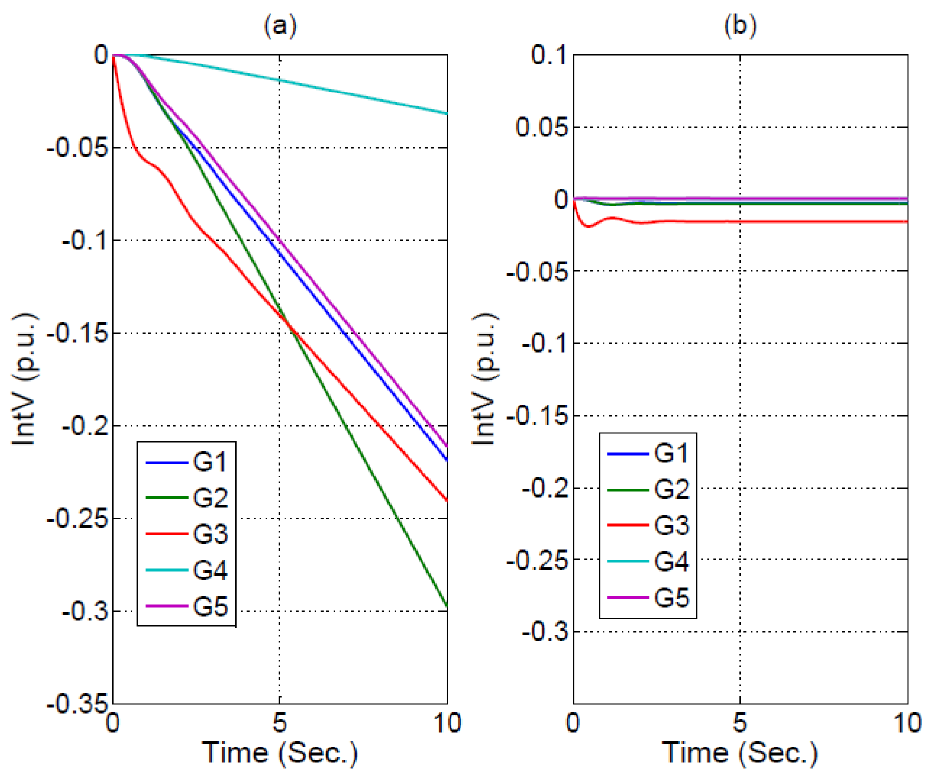
Communications Setup Table:

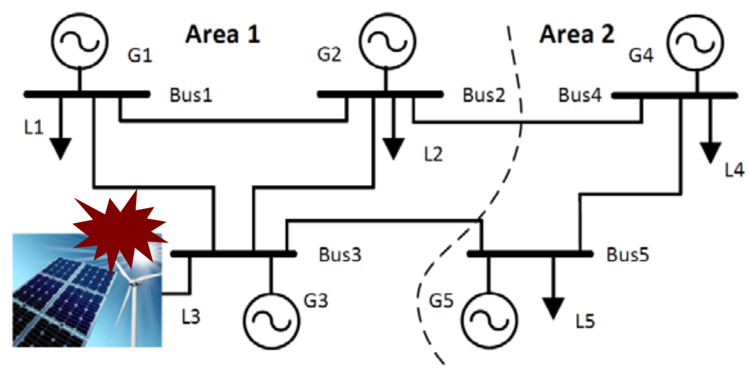
From	EAGC_Gen	EAGC	EAGC_L/Dist	EAGC
To	EAGC	EAGC_Gen	EAGC	EAGC_L/Dist

Illustration of the Proposed QoR Analysis and Control

- Test system: the 5-bus system with the proposed stabilization control
- Closed-loop system response under 0.1 p.u. disturbance at L3

Effective Control of IntV by E-AGC (a) before; (b) after





- (a) before: inconstant IntVs, indicating problematic frequency QoR
- (b) after: constant IntVs, indicating recovered frequency QoR

Performance on Recovering the Nominal Frequency

Comparison between E-AGC and AGC (a) before control; (b) after E-AGC; (c) after AGC

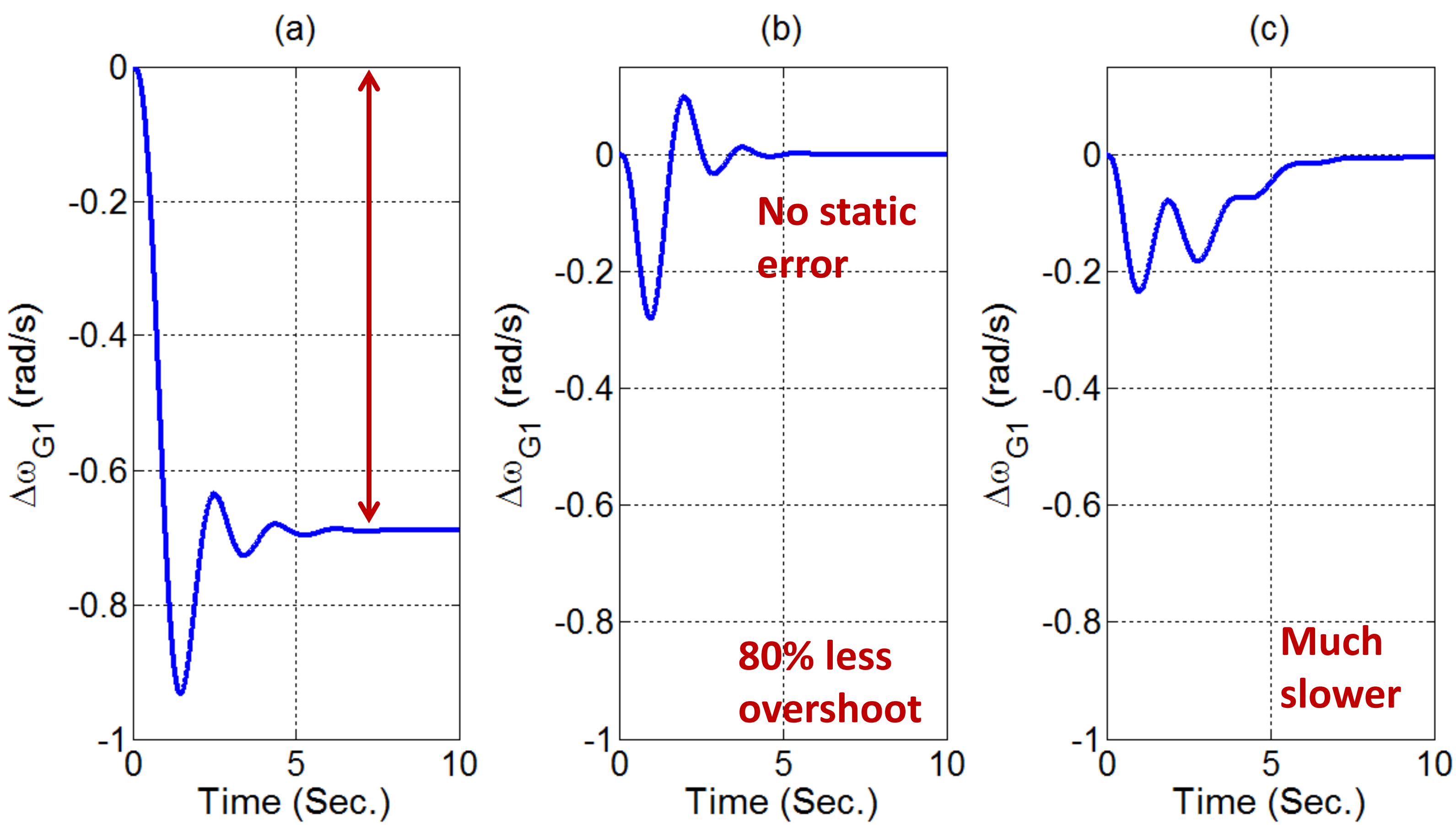
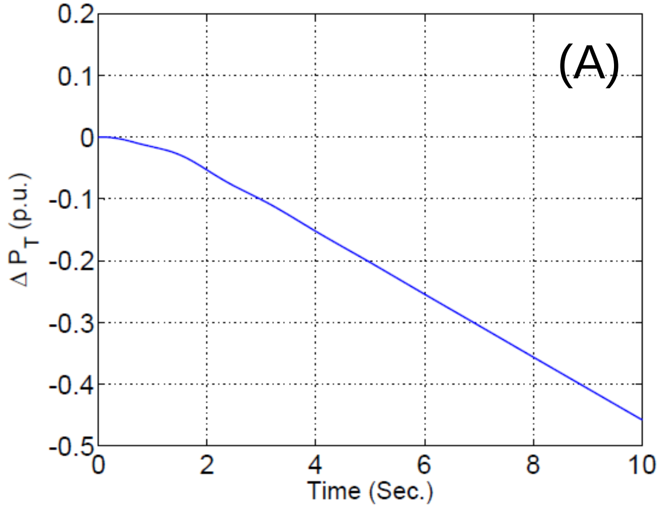
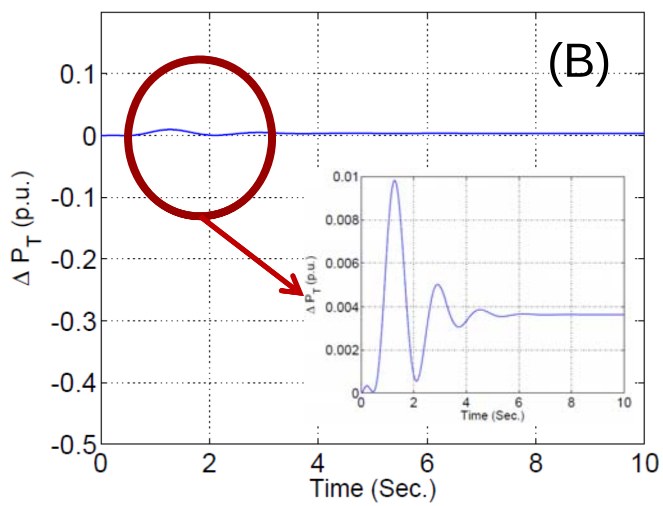


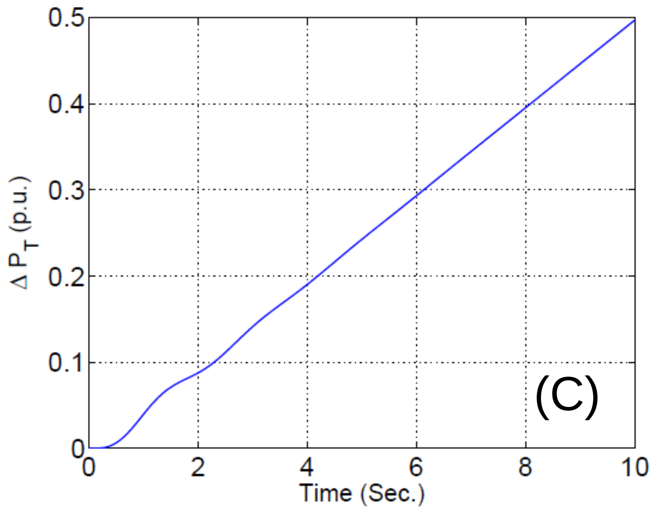
Illustration of Reduced Control Effort Needed for Stabilization by Combining with E-AGC

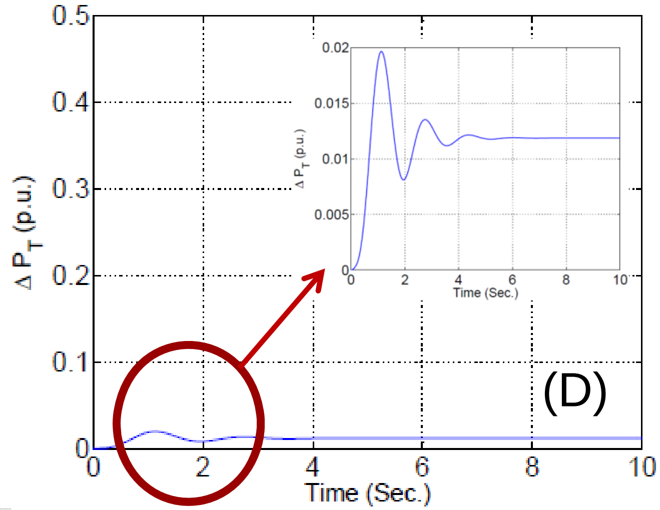




(A)
Stabilization control efforts needed by iBA-R1 before E-AGC applied

(B)
Stabilization control efforts needed by iBA-R1 after E-AGC applied





(C)
Stabilization control efforts needed by iBA-R2 before E-AGC applied

(D)
Stabilization control efforts needed by iBA-R2 after E-AGC applied

Summary

- The “structure” of a multi-layered dynamic system created by relative dynamics of its (groups of) components and their dynamic interactions
- One novel QoR control (E-AGC) is proposed for acceptable QoR, which eliminates the conserved net power imbalance without excessive control effort
- The proposed model-based E-AGC approach doesn’t require steady state assumption, then it can be applied to the system with time varying persistent disturbance
- Only IntV information is communicated. It requires less sensing and communication effort and can be practically implemented in large scale system
- Generalized modules and communication infrastructure in SGRS are defined and it will be one of the SGRS applications in the future.

Reference

1. X. Miao, K.D. Bachovchin, M. D. Ilic . Effect of load type and unmodeled dynamics in load on the equilibria and stability of electric power system. Submitted to CDC 2015
2. M.D. Ilic and Qixing Liu. Toward standards for model-based control of dynamic interactions in large electric power grids. In Signal Information Processing Association Annual Summit and Conference (APSIPA ASC) 2012, pages 1–8, 2012.
3. M. D. Ilic and J. Zaborszky, Dynamics and Control of Large Electric Power Systems. New York: Wiley Interscience, 2000
4. Q. Liu. Wide-Area Coordination for Frequency Control in Complex Power Systems. Ph.D. Thesis, Carnegie Mellon University, Aug 2013.
5. M. D. Ilic and X.S. Liu. A simple structural approach to modeling and analysis of the inter-area dynamics of the large electric power systems: Part I– linearized models of frequency dynamics. In Proceedings of the 1993 North American Power Symposium, pages 560–569, Washington, DC, October 1993.

Questions?