Toward Plug-and-Play Standards for Dynamics in the Changing Electric Energy Systems

Marija Ilić, Professor
Carnegie Mellon University
milic@andrew.cmu.edu

PSERC

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Acknowledgements

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- Thanks to the industry advisors on S-55 for providing input; particular thanks go to ISO-NE and RTE.

- Ideas in this talk have evolved over time: S.X. Liu at MIT , Qixing Liu, Milos Cvetkovic , Kevin Bachovchin and Stefanos Baros and Xia Miao.

- This past and on-going work has jointly helped us re-think the modeling of power systems and has gradually led to a unified modeling approach used to propose possible plug-and-play dynamic standards.

Outline

- What are dynamic standards?
- Why do we need them?
- How do we propose to define them formally?
- Examples of what has been done so for.
- Open questions and future work.

What are dynamic standards?

- Quantifiable performance criteria/metrics/protocols needed to support automated control of hard-to-predict (uncertain) deviations from scheduled conditions (power profiles and/or equipment status).
- Needed to avoid:

    - operational problems (short-term instabilities)

    - long-term instabilities (resource adequacy, financial instabilities.) Not discussed in this talk.

- Existing standards--- notable AGC principles.
- Define new standards for the changing industry by evolving from the existing standards (based on similar high-level principles).

Why dynamic standards beyond the existing?

- Difficult to integrate smart technologies reliably.
- Necessary because the system is operated much more dynamically than in the past. Deviations from predictable conditions much more significant (larger and faster).
- Potentially basic means of enabling innovation.
- Smarts *can* help reliable operation provided systematic performance metrics are defined and implemented.
- Like it or not, the industry must rely more on flexible automation and less on preventive worst-case scenarios for ensuring reliability. Real difficult change of paradigm.
- Today’s dynamic standards are incomplete and not designed for guaranteeing stability.

Problems with today's standards

- Time scales incomplete, mainly quasi-static or static
- Faster dynamic characteristics, new for power systems but not considered in today's standards
- Integration of renewable generation resources Installation of power electronics devices (FACTS, SVC, HVDC, DFIG)
- Integration of electric energy storage devices (battery, flywheels)
- Integration of adaptive loads
- Integration of sensing and communication technologies

Toward standards for smart grids

- Objective: Support design of systematic control for predictable dynamic performance
- Innovation challenges

    - No single entity charging the entire design, possibly different for micro-grids

    - The power network spreads over vast geographical areas, creating challenges for sensing, communication and estimation

- Key issues

    - Centralized vs decentralized infrastructure (what information must be exchanged)

    - What needs to be controlled

    - Where to place sensors and why

    - What needs to be communicated

Gradual evolution of existing standards?

- By building on the principles underlying today's standards.
- Automatic generation control (AGC)

  - control area level (plug-and-play)

  - standard in terms of energy deviation over the time of interest; and rate of change of energy—power—sent to the rest of the system
- Voltage-ride-through for wind power plants

  - component level (plug-and-play)

  - standard is critical clearing time –directly interpretable in terms of accelerated and decelerated energy during fault and following the fault, respectively
- We propose to evolve toward a family of standards with the same common underlying high-level principles

Starting principle -- AGC control standards

- Control Performance Standard (CPS) 1 and 2 [1]

  - Defines an error signal for AGC to represent increment of energy exchanged with neighboring areas

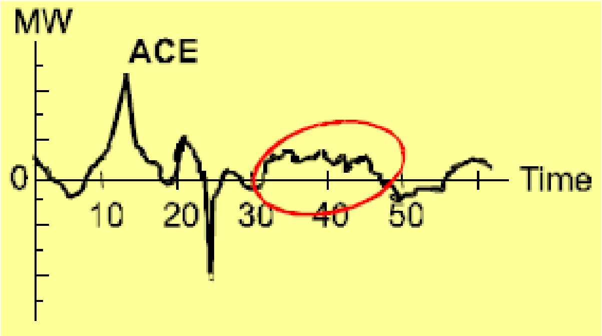
  - Error Signal: Area Control Error (ACE)

  - CPS1 requires ACE to cross zero every 10 minutes

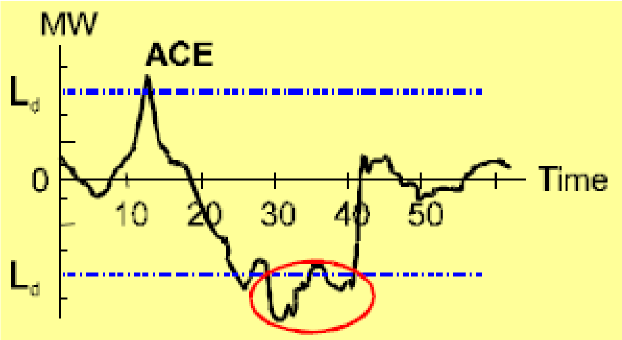
  - CPS2 requires the 10-min averaged ACE to stay within limits

$$ACE_i = \Delta P_{tie,i} - 10\beta_i \Delta f_i$$

CPS1



CPS2



[1] http://www.nerc.com

Potential dynamical problems without standards for guaranteed performance [2]

	Dynamical problems						
		Small signal instability	Transient instability	SSR	SSCI	Poor frequency regulation	Poor voltage regulation
Types of components contributing to instability	Synchronous generators	?	?	?	?	?	?
	Wind generators	?	?	?	?	?	?
	Solar plants	?	?	?	?	?	?
	FACTS	?	?	?	?	?	?
	Storage	?	?	?	?	?	?

Table 1---Possible unacceptable temporal and/or spatial interactions.

[2] Marija D. Ilić and Stefanos Baros, PSERC Draft Report, Project S-55, November 2015.

Objectives of dynamic standards [2,3]

- (Near-) complete set of dynamic standards to ensure reliable temporal response

  - avoid sub-synchronous resonance (electro- mechanical (SSR), electromagnetic resonance (SSCI);

  - response to very fast large equipment status changes (contingencies, faults)-transient stabilization

  - response to small fast fluctuations (small signal frequency and voltage stabilization)

  - response to relatively slow (quasi-stationary) power imbalances (frequency, voltage regulation)

- (Near-) complete set of dynamic standards to ensure reliable geographical (spatial) response

  - avoid oscillatory dynamic interactions (instabilities)

  - avoid inter-area oscillations

[3] Marija D. Ilić and Qixing Liu, "Toward Standards for Model-Based Control of Dynamic Interactions in Large Electric Power Grids", APSIPA, Dec 2012, Holywood, CA.

Common principles for dynamic standards

- Physics-based multi-layered modeling defines standards capable of supporting reliable operations.
- Must be met by *all* (groups of) components comprising any given electric energy system (today's or emerging).
- Performance metrics support control of dynamic operations.
- Standards should be simple ("plug-and-play) to implement.
- Clear tradeoff between simplicity and performance.
- Standards should support implementation of "best smarts".
- Non-unique– as long as they meet the pre-specified performance, any combination of technology is acceptable.
- AGC and voltage-ride-through are examples of what is needed; they do not meet all these requirements. Need enhancements. Plus new standards are needed, but must draw on these common principles.

Designing near-complete dynamic standards[4]

- Structure-preserving modeling; explicit interaction variables for specifying interfaces (basis for standardization).
- Models capture both temporal and spatial granularity.
- Near-complete family of temporal models

  - Family of carefully designed reduced-order models with clear physical interpretation/assumptions/functionalities

  - Feed-forward power inputs viewed as nominal operating conditions around which deviations occur

  - Temporal deviations specified in terms of energy and power increments

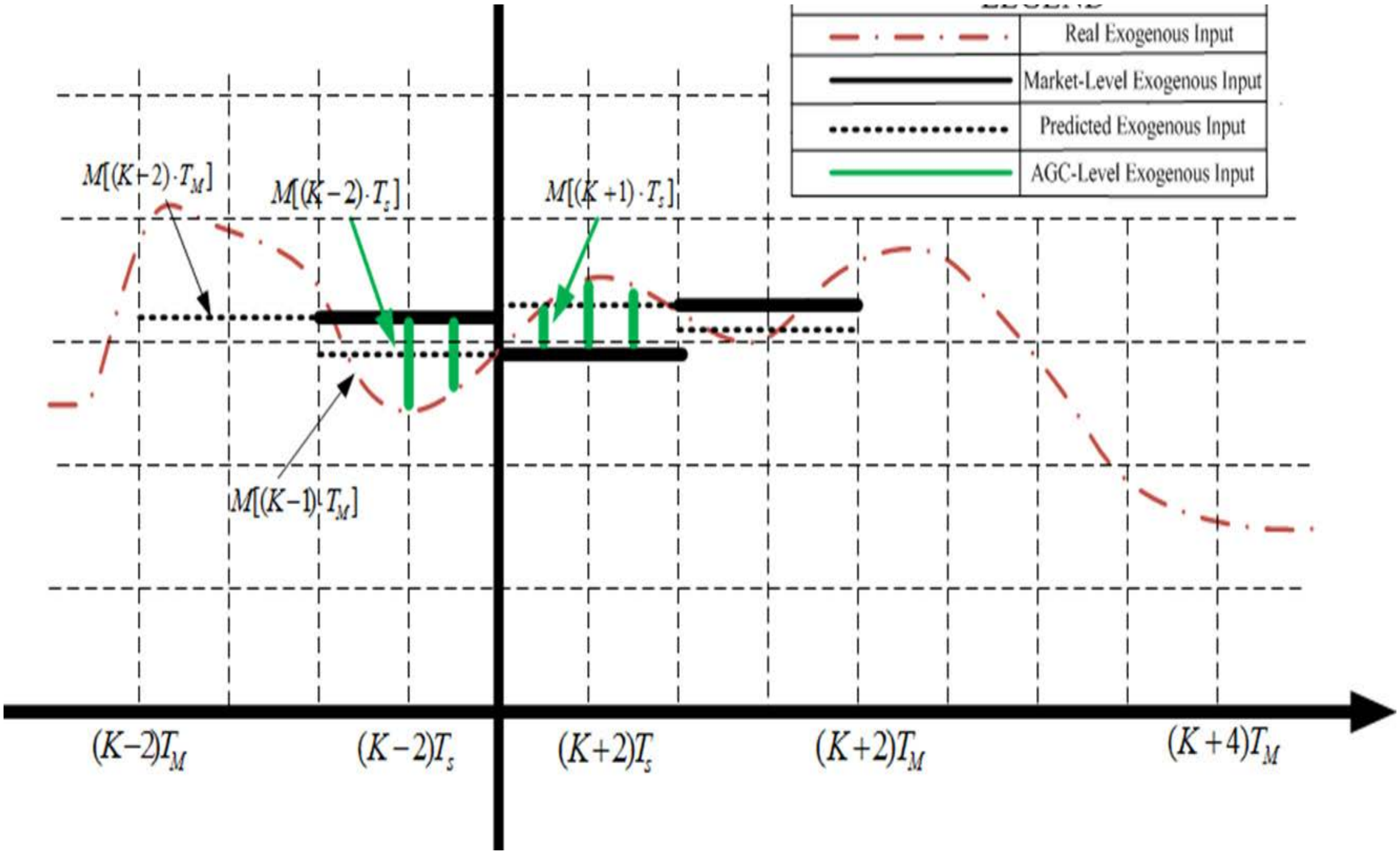
- Near-complete family of spatial models

  - Each layer within the multi-layered architecture must specify its spatial interactions with the rest of the system (any iBA-component, region, interconnection)

[4] Marija Ilic, Near-complete spatial and temporal dynamic standards, IEEE PES 2015 (under submission).

Multi-temporal dynamic disturbances [5]

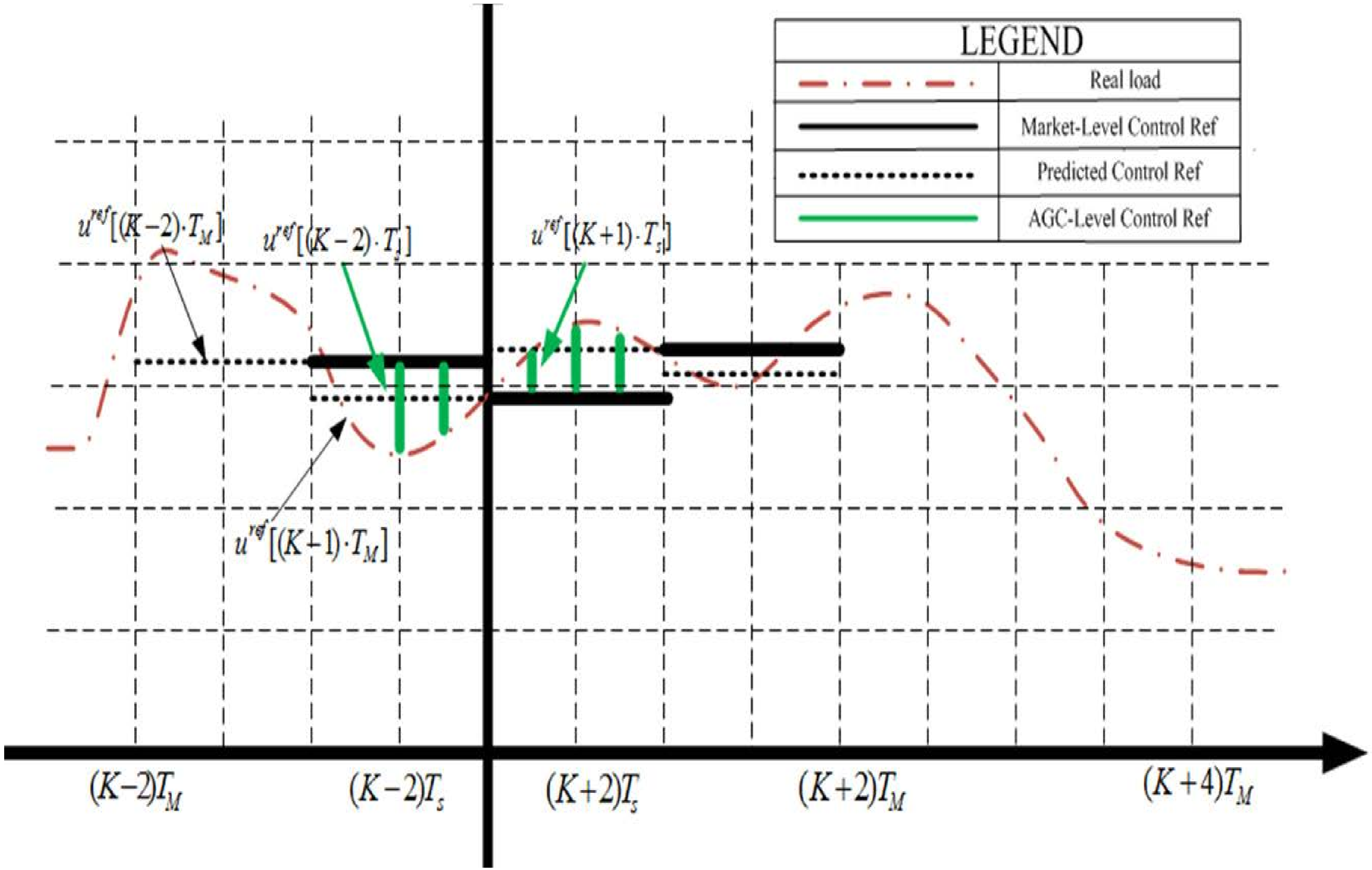
$$m_i(t) = M_i[KT_M] + M_i[kTs] + \Delta m_i(t)$$



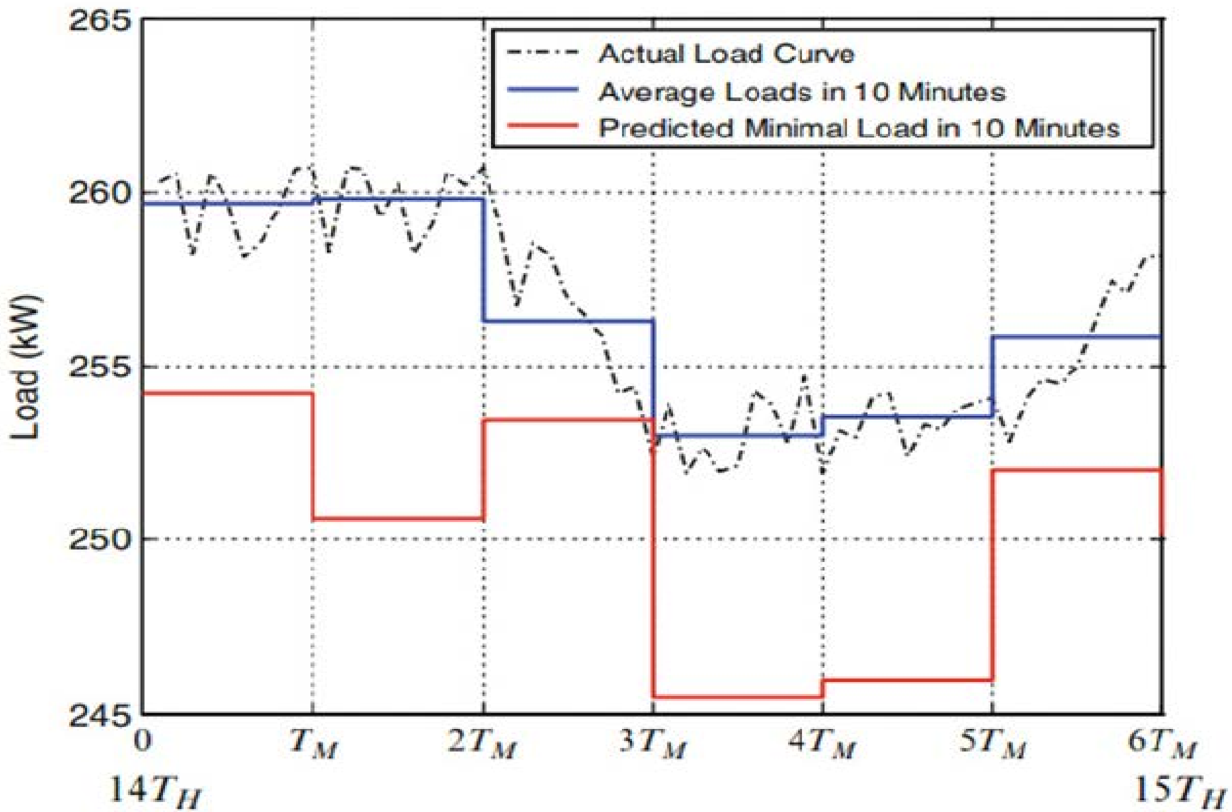
[5] Marija Ilic et al, Tutorial paper, IEEE CDC 2014.

Multi-temporal dynamic control

$$u_i(t) = u_i(t)^{stab} + u_i^{ref}[kT_s] + u_i^{ref}[KT_M]$$



Stochastic non-zero mean dynamic disturbances
The new challenge!

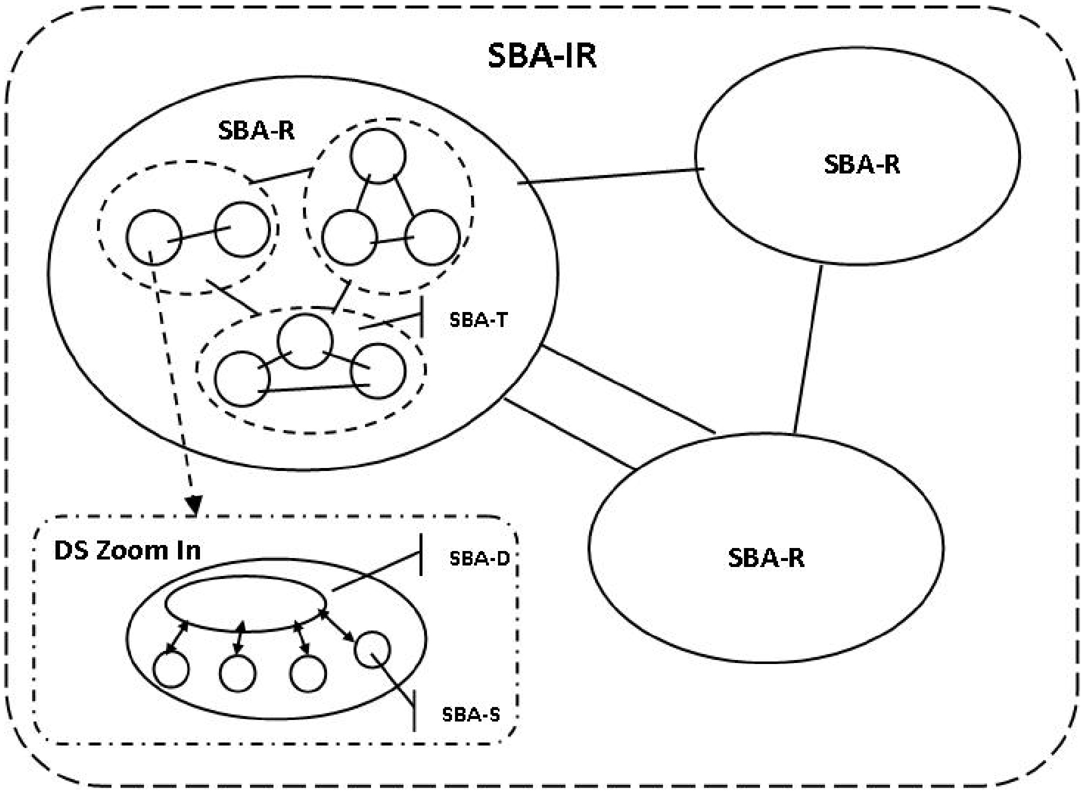


- Can no longer design AGC assuming zero-mean deviations; cannot assume steady state when fast dynamics unstable!
- Must have standards to manage spatial and temporal disturbances.

Interaction variables –key to multi-layered modeling

- Multi-layered dynamic model useinteraction variables explicitly
- Novel state-space transformation to local and interaction variables.
- Dynamic state space formulation key to control design (not essential for analysis)
- Standard specifications set in terms of interaction variables
- The “plug-and-play” design for provable performance becomes possible
- Common principles.
- Proposed plug-and-play dynamic standardization examples (Enhanced AGC (E-AGC) for guaranteed small signal frequency stabilization and regulation; Improved secondary voltage control; Transient stabilization; Stabilization of electro-mechanical sub-synchronous SSR; Stabilization of elector-magnetic sub-synchronous control instabilities (SSCI)).

General structure of electric energy systems[6]



-SBA: Smart Balancing Authorities (Generalization of Control Area)

-IR: Inter-Region

-R: Region

-T: Tertiary

-D: Distribution

-S: Smart Component

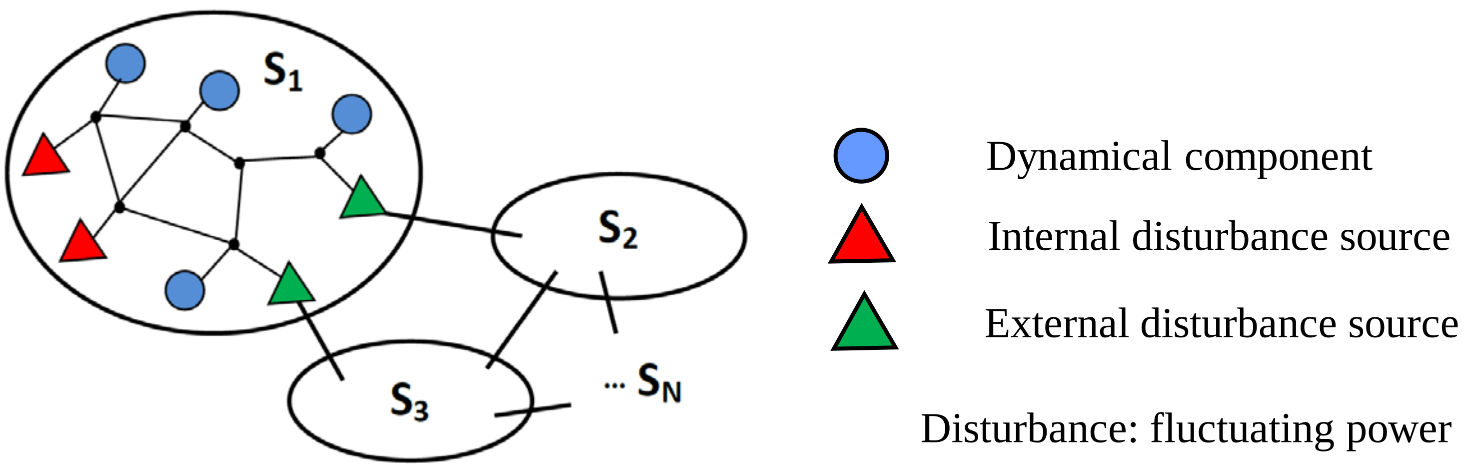
- Note: SBAs renamed to iBAs (suggestion by a PSERC member)

[6] Ilic, M., "Dynamic Monitoring and Decision Systems for Enabling Sustainable Energy Services", Network Engineering for Meeting the Energy and Environmental Dream, Scanning the Issue, Proc. of the IEEE.

Multi-layered interconnected dynamic model

- System Model Structure[7,8]
  - Component-> Subsystem-> Interconnected system
  - Modeling reviewed for the distributed control design to stabilize and regulate small-signal linearized dynamics

S_i Subsystem-level intelligent Balancing Authority (iBA)

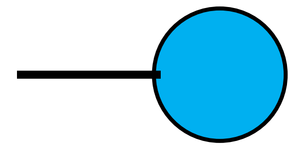


Disturbance: fluctuating power input/output

[7] Ilic, M.D. and S.X. Liu, Hierarchical Power Systems Control: Its Value in a Changing Electric Power Industry, Springer-Verlag London Limited Series, Advances in Industrial Control,1996.

[8] Qixing Liu, "A Large-Scale Systems Framework for Coordinated Frequency Control of Electric Power Systems, ECE Department, Carnegie Mellon University, December 2013.

Component-level model structure



- Standard state space model
  - A typical synchronous generator model

$$\begin{bmatrix}\Delta\dot{\delta}_G\\ \Delta\dot{\omega}_G\\ \Delta\dot{P}_T\\ \Delta\dot{a}\end{bmatrix}=\begin{bmatrix}0 & \omega_0 & 0 & 0\\ 0 & -\frac{D}{M} & \frac{1}{M} & 0\\ 0 & 0 & -\frac{1}{T_t} & \frac{Kt}{T_t}\\ 0 & -\frac{1}{T_g} & 0 & -\frac{r}{T_g}\end{bmatrix}\begin{bmatrix}\Delta\delta_G\\ \Delta\omega_G\\ \Delta P_T\\ \Delta a\end{bmatrix}+\begin{bmatrix}0\\0\\0\\ \frac{1}{T_g}\end{bmatrix}\Delta\omega_G^{ref}+\begin{bmatrix}0\\ -\frac{1}{M}\\0\\0\end{bmatrix}\Delta P_G,$$

Table 1: Parameters interpretation (p.u.)

δ_G, ω_G	angular position and rotating freq.
P_T, a	produced power and valve openning
P_G	output power

  - Generalized standard state space model

$$\dot{x}_{c,i} = \underbrace{A_{c,i}x_{c,i}}_{local\ \ dynamics} + \underbrace{\sum_{j=1}^{N_c} A_{c,ij}x_{c,j}}_{coupling} + \underbrace{B_{c,i}u_{c,i}}_{control}, \qquad x_{c,i}(t_0) = x_{ci0}$$

  - Local $A_{c,i}$ has **rank deficiency** to the magnitude at least **1**

Component-level model

- ***Interaction variable***

$$z_{c,i} = T_{c,i} x_{c,i};$$

$$T_{c,i} A_{c,i} = 0.$$

- It spans the null space of $A_{c,i}$

- A linear combination of states $x_{c,I}$
  - An aggregation variable

- ***Dynamic model***

$$\dot{z}_{c,i} = T_{c,i} \sum_{j=1}^{N_c} A_{c,ij} x_{c,j} + T_{c,i} B_{c,i} u_{c,i},$$

- ***Physical interpretation***
  - Driven only by **external coupling** and **internal control/disturbances**
  - **Invariant** in a **closed/disconnected** and **uncontrolled/undisturbed system**
  - Result of the **conservation of power law at the component level**

Subsystem-level model

- Standard state space model

$$\dot{x}_{a,k} = \underbrace{A_{a,k}x_{a,k}}_{local\ \ dynamics} + \underbrace{\sum_{h=1}^{N_a} A_{a,kh}x_{a,h}}_{coupling} + \underbrace{B_{a,k}u_{a,k}}_{control}, \quad x_{a,k}(t_0) = x_{ak0},$$

$$x_{a,k} = \begin{bmatrix} x^k_{c,1} \\ x^k_{c,2} \\ \vdots \\ x^k_{c,N^k_c} \end{bmatrix} \text{ and } u_{a,k} = \begin{bmatrix} u^k_{c,1} \\ u^k_{c,2} \\ \vdots \\ u^k_{c,N^k_c} \end{bmatrix}.$$

  - Local $A_{a,k}$ has **rank deficiency** to the magnitude at least **1**

Subsystem-level model

- ***Interaction variable***

$$z_{a,k} = T_{a,k} x_{a,k};$$

$$T_{a,k} A_{a,k} = 0.$$

-A linear combination of states $x_{a,k}$

-It spans the null space of $A_{a,k}$

- ***Dynamic model***

  -An aggregation variable

$$\dot{z}_{a,k} = T_{a,k} \sum_{h=1}^{N_a} A_{a,kh} x_{a,h} + T_{a,k} B_{a,k} u_{a,k},$$

- ***Physical interpretation***
  - Driven only by **external coupling** and **internal control/disturbances**
  - **Invariant** in a **closed/disconnected** and **locally uncontrolled/undisturbed system**
  - Reflects the **Conservation of Power** at the disconnected **Subsystem level**

Interconnected system-level model

- Standard state space model in general

$$\dot{x}_s = \underbrace{A_s x_s}_{local\ \ dynamics} + \underbrace{B_s u_s}_{control}, \quad x_s(t_0) = x_{s0},$$

$$x_s = \begin{bmatrix} x_{c,1} \\ x_{c,2} \\ \vdots \\ x_{c,N_c} \end{bmatrix} = \begin{bmatrix} x_{a,1} \\ x_{a,2} \\ \vdots \\ x_{a,N_a} \end{bmatrix} \quad \text{and} \quad u_s = \begin{bmatrix} u_{c,1} \\ u_{c,2} \\ \vdots \\ u_{c,N_c} \end{bmatrix} = \begin{bmatrix} u_{a,1} \\ u_{a,2} \\ \vdots \\ u_{a,N_a} \end{bmatrix}.$$

  - No external coupling term
  - Local A_s has **rank deficiency** to the magnitude at least **1**

Interconnected system-level model

- ***Interaction variable***

$$z_s = T_s x_s,$$

- A linear combination of states x_s
  - An aggregation variable

$$T_s A_s = 0.$$

-It spans the null space of A_s

- ***Dynamic model***

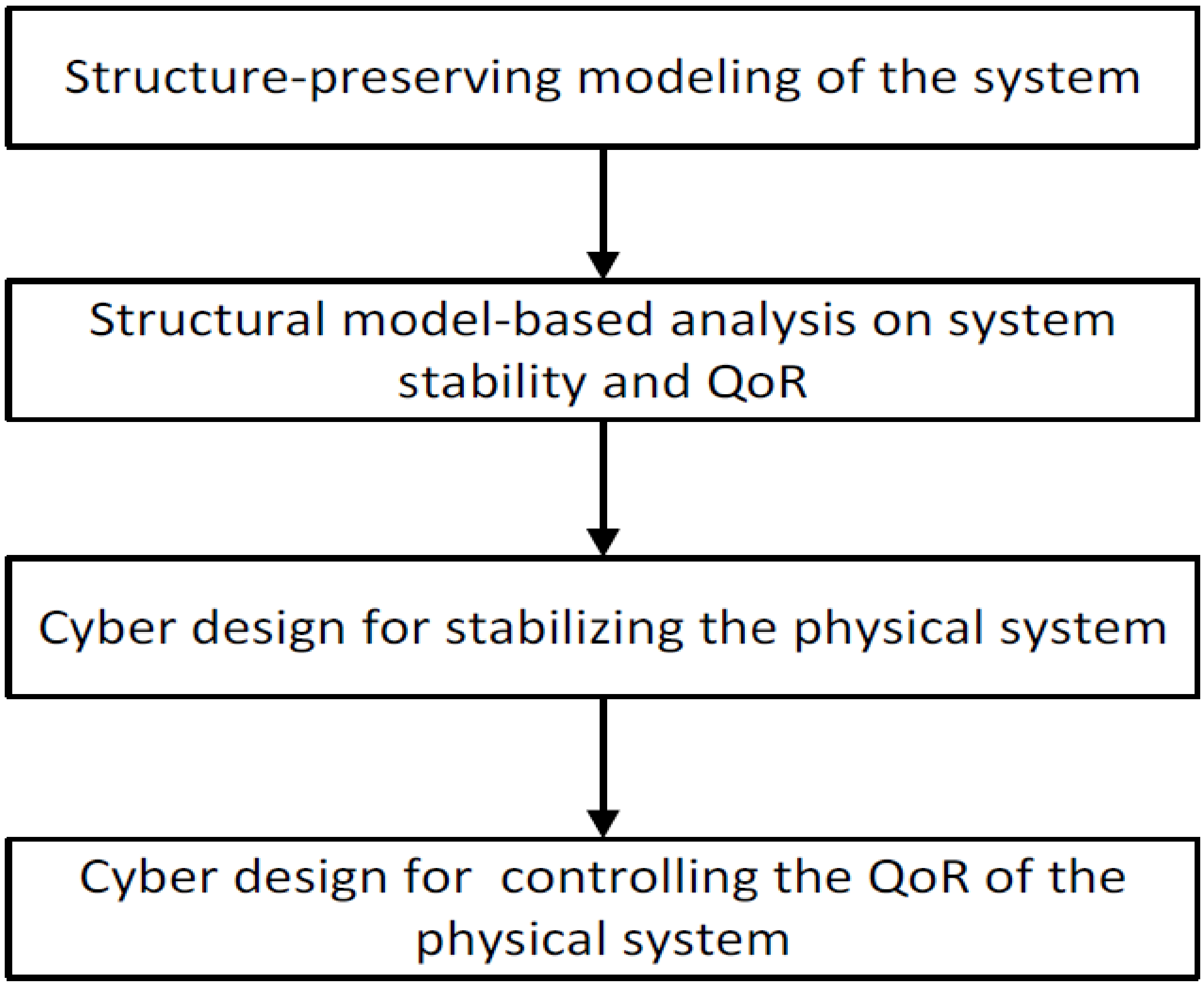
$$\dot{z}_s = T_s B_s u_s,$$

- ***Physical interpretation***
  - Driven only by internal control
  - Invariant in an uncontrolled system
  - Reflects the Conservation of Power at the Interconnected System Level

A multi-layered system stabilization

- Control objective
  - Stabilization of the interconnected system
  - Eigenvalues of the closed-loop system negative real parts
- Multi-layered control approach
  - Component-level: distributed control with limited coordination
  - Subsystem-level: distributed control with limited coordination
  - Interconnected system-level: coordinated control

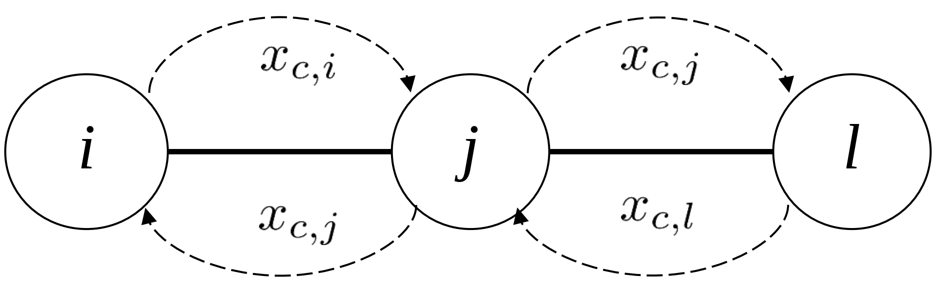
Multi-layered approach to dynamic control



Component-level: distributed control with limited coordination

- State-of-the-art
  - Control local dynamics; Control the coupling term
  - Sense local states $x_{c,I}$
  - Communicate $x_{c,i}$ only to neighboring components

- *Local control* $u^l_{c,i} = -K^l_{c,i} x_{c,i}$
- *Global control* $u^g_{c,ij} = -K^g_{c,ij} x_{c,j}, \quad j = 1, ..., N_c$
- *Closed-loop system* $\dot{x}_{c,i} = (A_{c,i} - B_{c,i}K^l_{c,i})x_{c,i} + \sum_{j=1}^{N_c}(A_{c,ij} - B_{c,i}K^g_{c,ij})x_{c,j}$
- *Communication infrastructure*



Subsystem-level: distributed control limited coordination

- State-of-the-art
  - **Control** interaction variable and its **first order** time derivative
  - **Sense** local states $x_{a,k}$
- No need for communication

- *Recall* $$\dot{z}_{c,i} = T_{c,i} \underbrace{\sum_{j=1}^{N_c} A_{c,ij} x_{c,j}}_{coupling\ \ included} + T_{c,i} B_{c,i} u_{c,i},$$

- *Local control* $$u_{a,k} = -L_{a,k1} z_{a,k} - L_{a,k2} \dot{z}_{a,k}$$

Interconnected system-level: centralized control

- State-of-the-art
  - Centralized control at the interconnected system-level
  - Sense full states x_s
- Communicate fully sensed x_s to the centralized control entity

- Full-state feedback control:

- Optimal control design:

$$u_s = -K_s x_s$$

$$\underset{u_s}{\text{minimize}} \quad J = \frac{1}{2}\int_{t_0}^{\infty} \left({x_s}^T Q_s x_s + {u_s}^T R_s u_s \right) dt$$

$$\text{subject to} \quad \dot{x}_s = A_s x_s + B_s u_s,\ x_s(t_0) = x_{s0}$$

- *Closed-loop system:*

$$\dot{x}_s = (A_s - B_s K_s) x_s, \quad x_s(t_0) = x_{s0};$$

Recent progress on interaction variable use

- Int-V based plug-and-play (competitive) control
  - Enhanced AGC (E-AGC) [9]
  - FACTS control of interarea oscillations [10]
  - VSD for demand participation in stabilization/regulating reserves [11]
  - SSR control [12]
  - Flywheel storage control for transient stabilization of wind power [13]
- *Cooperative control using int-V*
  - Int-V based transient stabilization [14]
  - Portfolia control-- wind power with storage [15]

[9] Qixing Liu, Marija D. Ilic Enhanced Automatic Generation Control (E-AGC) for Future Electric Energy Systems, Power and Energy Society General Meeting, July 2012, San Diego, CA, USA

[10] M.D. Ilic and S.X. Liu, "Direct Control of Inter-area Dynamics in Large Power Systems Using Flexible AC Transmission Systems (FACTS) Technology," U.S. patnt 5517 422, 1996.

[11] K. D. Bachovchin, "Design, Modeling, and Power Electronic Control for Transient Stabilization of Power Grids Using Flywheel Energy Storage Systems," Ph.D. dissertation, Carnegie Mellon University, PA, 2015.

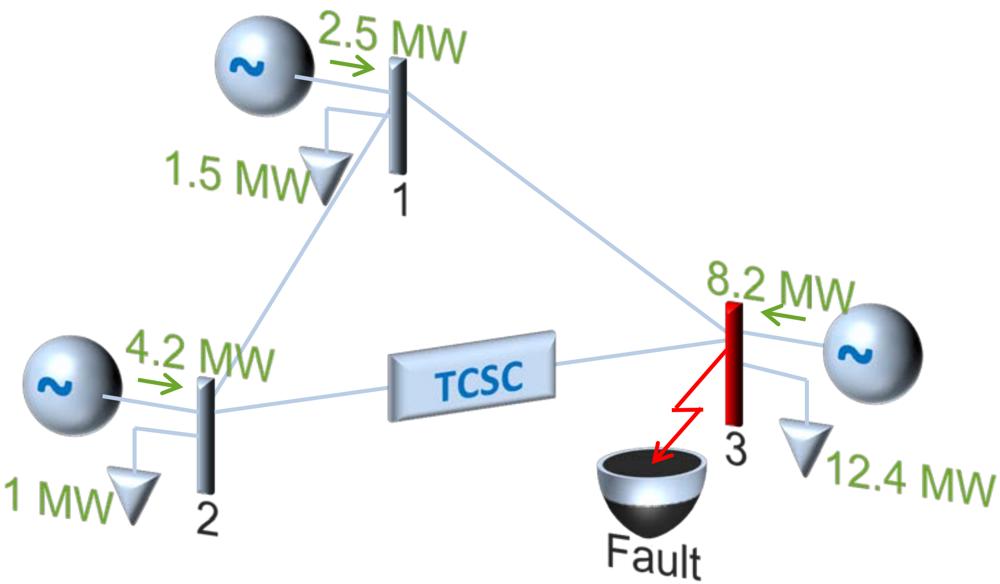
[12] Allen, E.H., J.W. Chapman and M.D. Ilic, "Effects of Torsional Dynamics on Nonlinear Generator Control," IEEE Transactions on Control Systems Technology, 4, 125-140, March 1996.

[13]S. Baros, M. Ilic, "Robust Ectropy-Based Control of a Wind DFIG", 2015 IEEE PES

[14] Cvetkovic, M., Ilic, M., Nonlinear Control for Stabilizing Power Systems During Major Disturbances, IFAC World Congress, Milano, Italy, August 28th-September 2nd, 2011.

[15] Stefanos Baros, PhD Thesis, ECE, Carnegie Mellon University, May 2015.

Non-linear control for storage devices



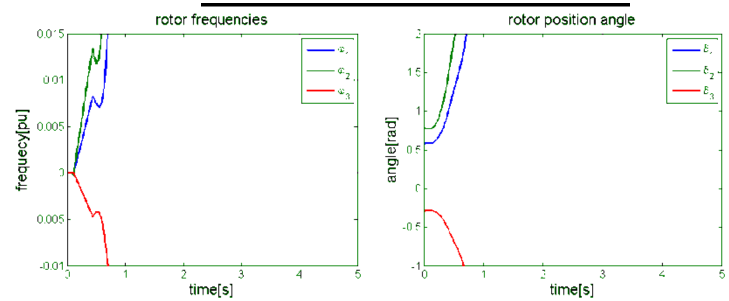
Fault:

- a short circuit at Bus 3
- created at $t = 0.1s$
- cleared at $t = 0.43s$

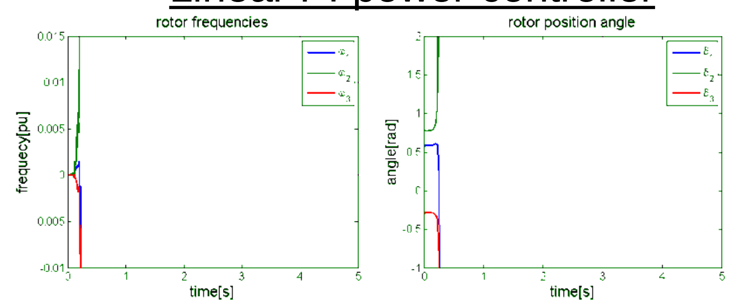
Critical clearing time:

$$T_{CCT} = 0.25s$$

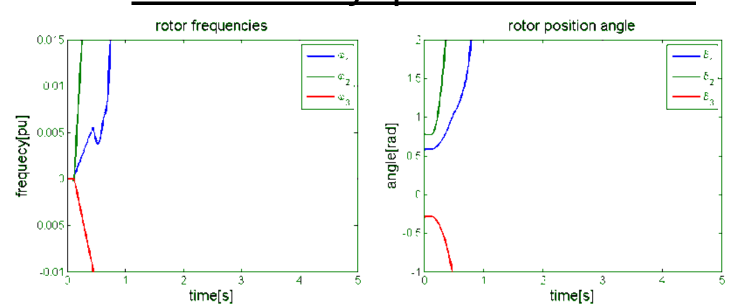
No controller on TCSC



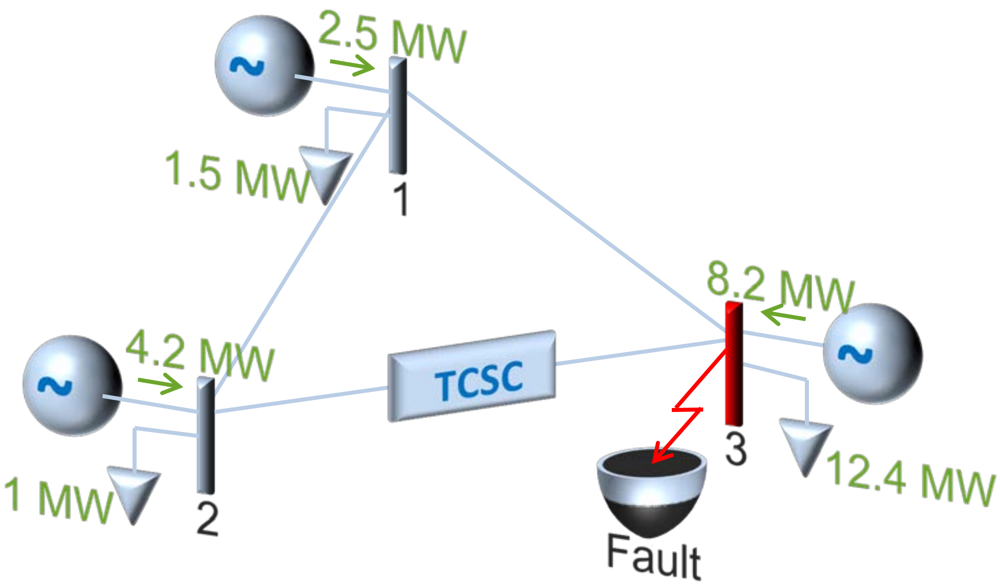
Linear PI power controller[2]



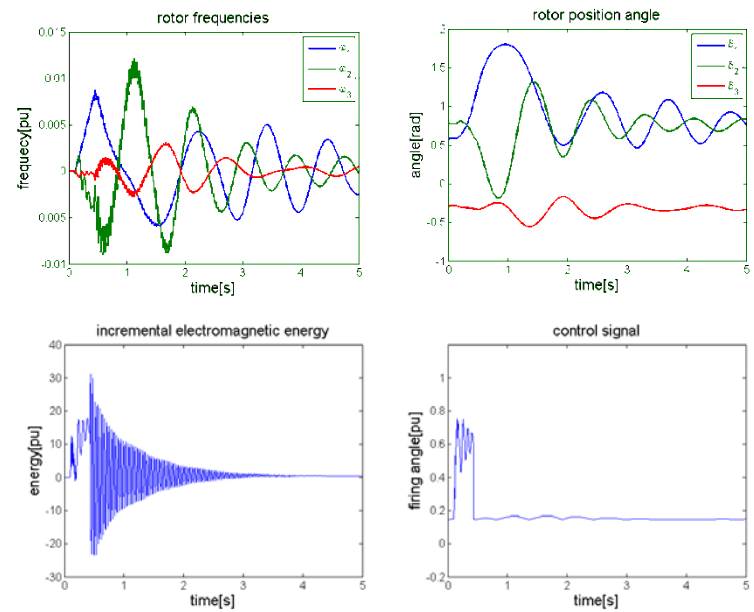
Nonlinear Lyapunov controller[3]



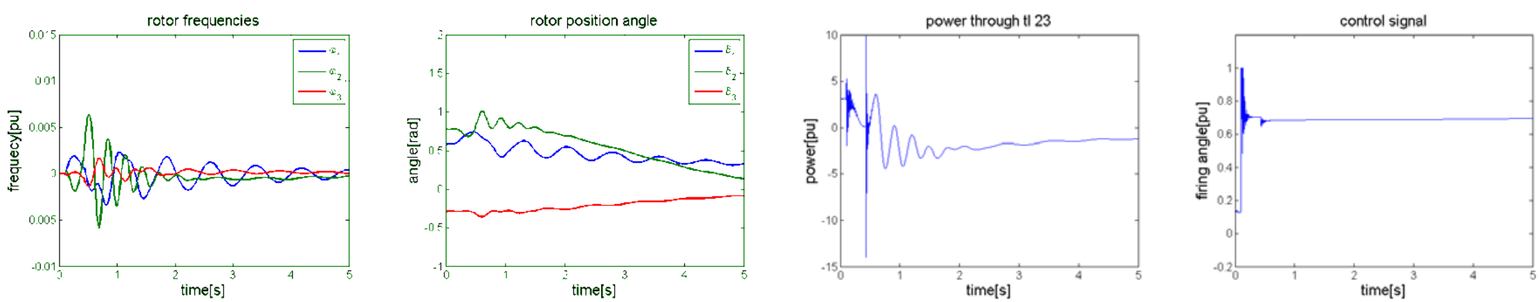
Use of interaction variables in strongly coupled systems (SSCI control)



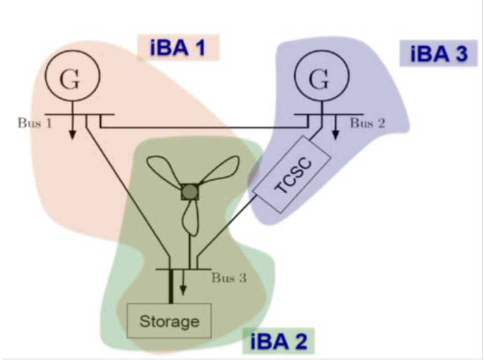
***Interaction variable choice 1*:**



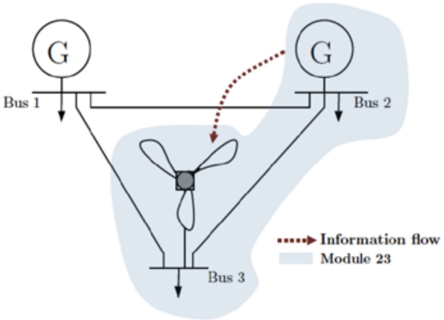
Interaction variable choice 2:

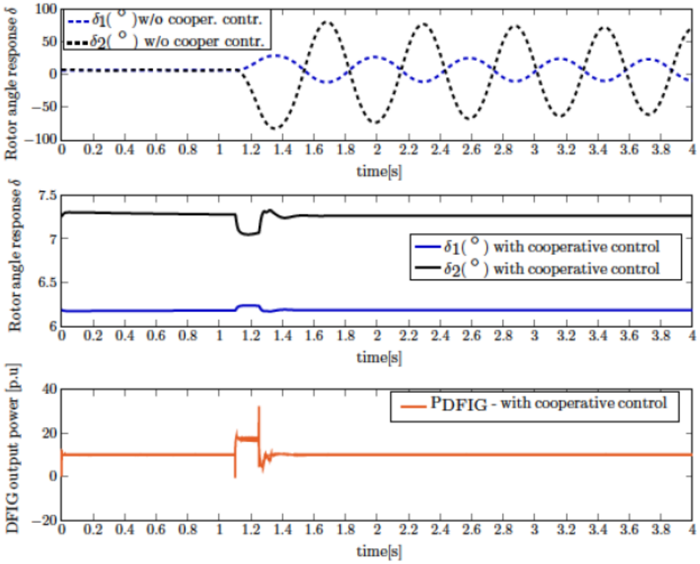


Transient stabilization, cooperative iBAs



Non-unique portfolia





Fault-ride-through requirements met

Generator 2 remains transiently stable with **no oscillations** (compared with the case with no DFIG control)

first swing has **smaller magnitude** → important for first swing instability

DFIG's with energy storage **can support the grid in many ways with appropriate control**

Cooperative first-swing stabilization

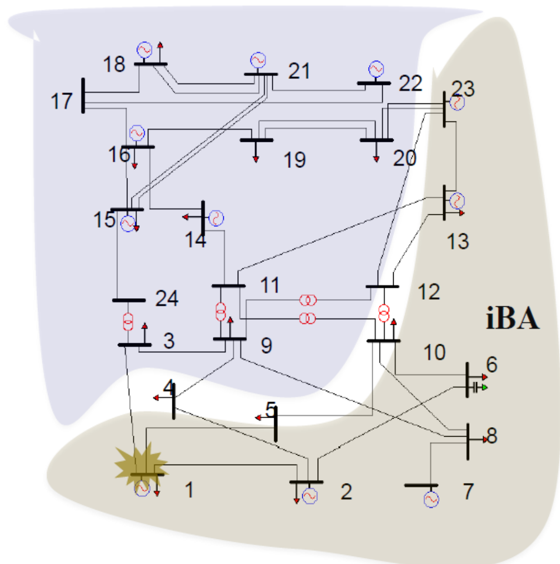
S.Baros, M.Ilić "Robust Ectropy-Based Control of a Wind DFIG with an Integrated Energy Storage for Transient Stabilization and MPPT", *2015 IEEE PES General Meeting (GM)*

Forming iBAs—top-down [16]

Given disturbance
Tripping of generator 1

TABLE I
CONTINGENCY CONSIDERED ON
THE IEEE RTS 24 BUS SYSTEM

CONTINGENCY (CATEGORY B)	DURATION (secs)
Tripping of generator 1 after 3-phase fault on its terminal bus	0.17



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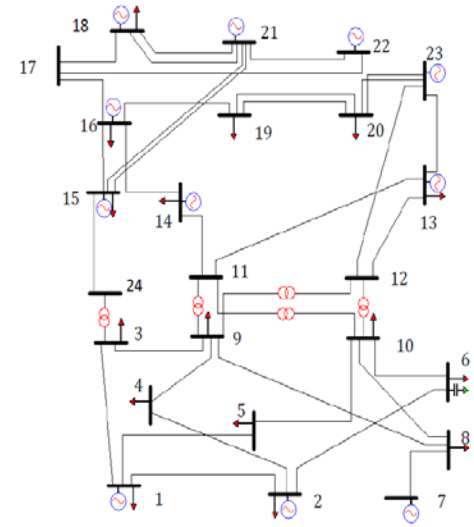
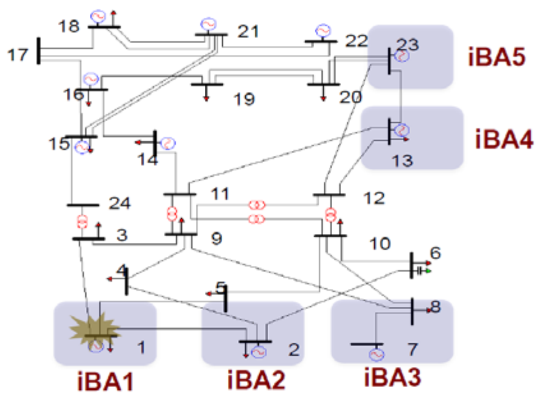


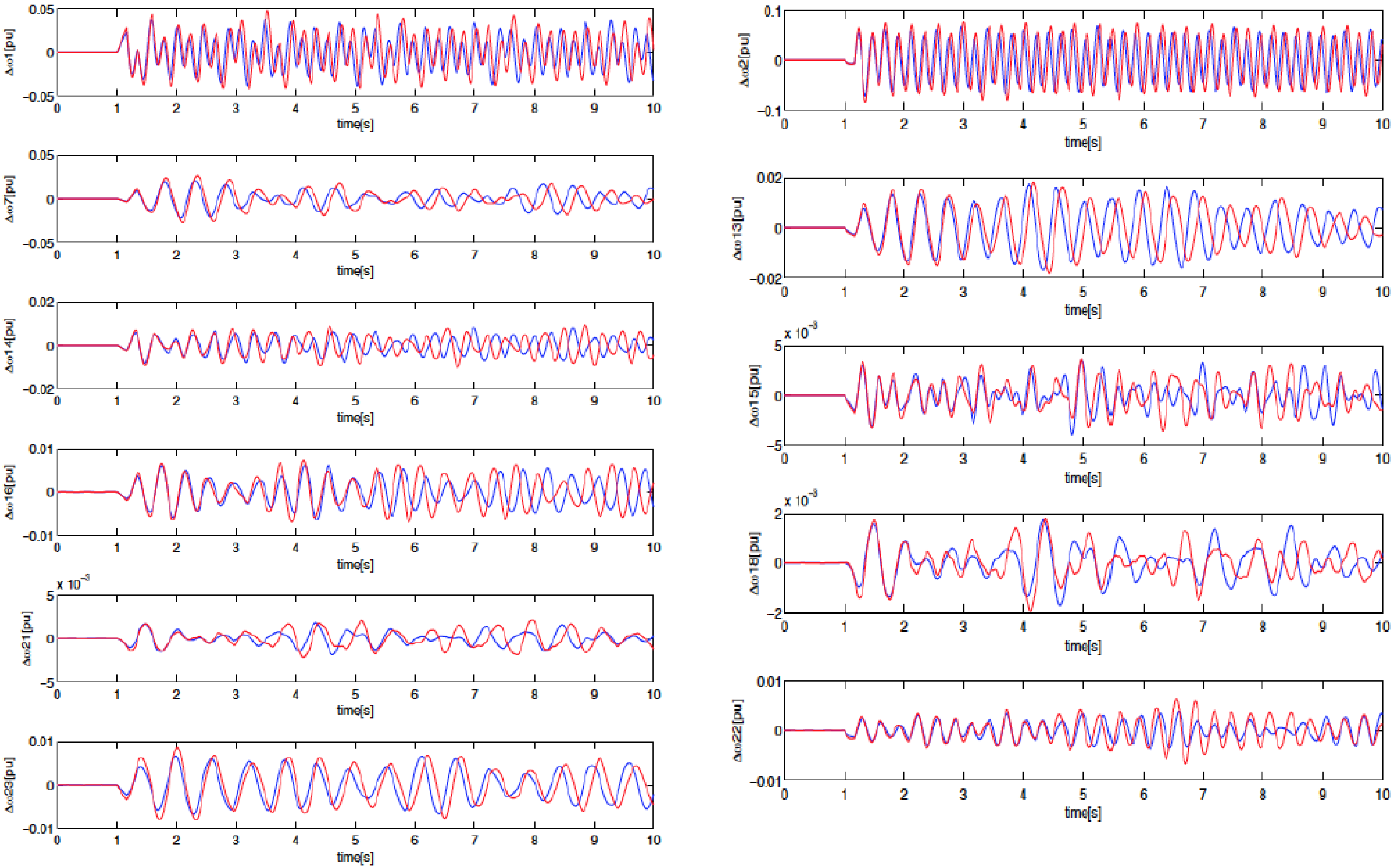
Competitive approach to meeting the standard



S.Baros, M.Ilic intelligent Balancing Authorities (iBAs) for Transient Stabilization of Large Power Systems
IEEE PES General Meeting 2014

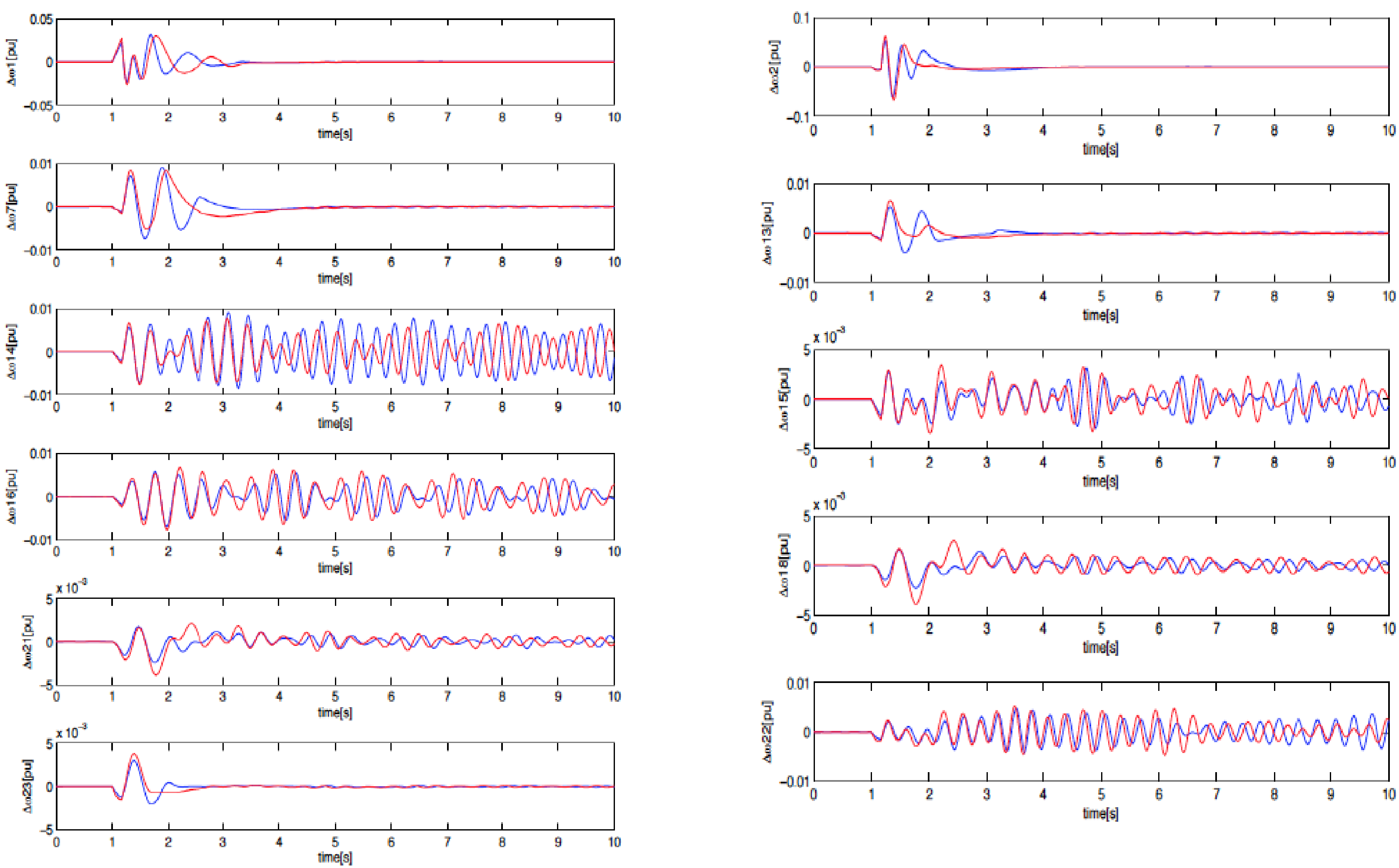
Response-no transient stabilization standard

Red - high load; Blue - low load

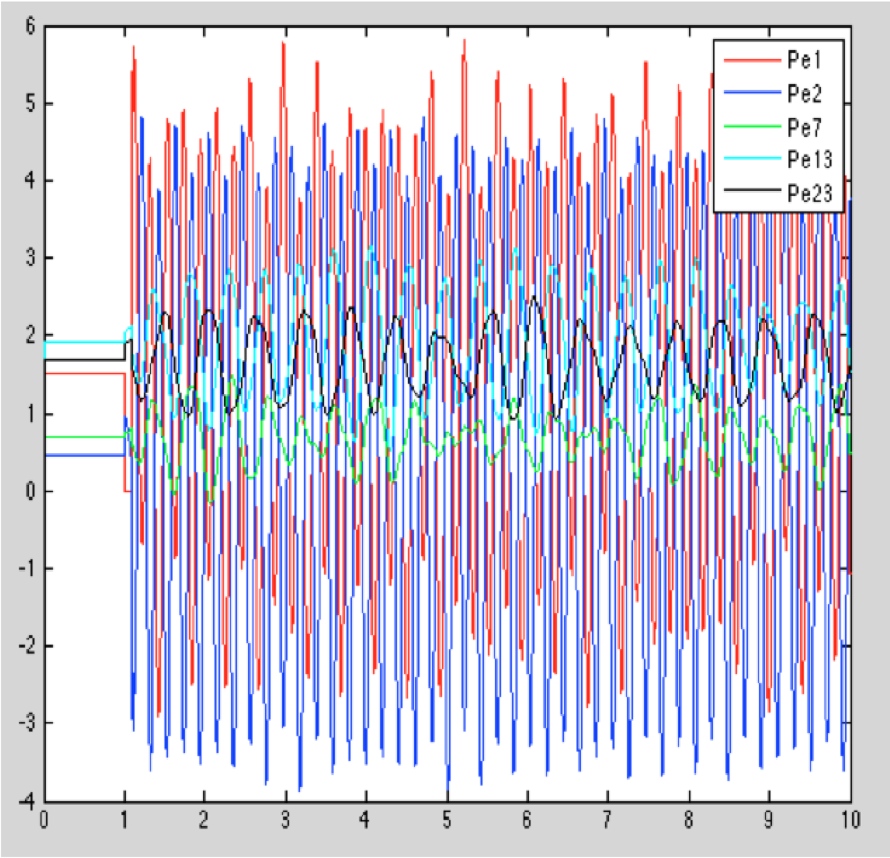


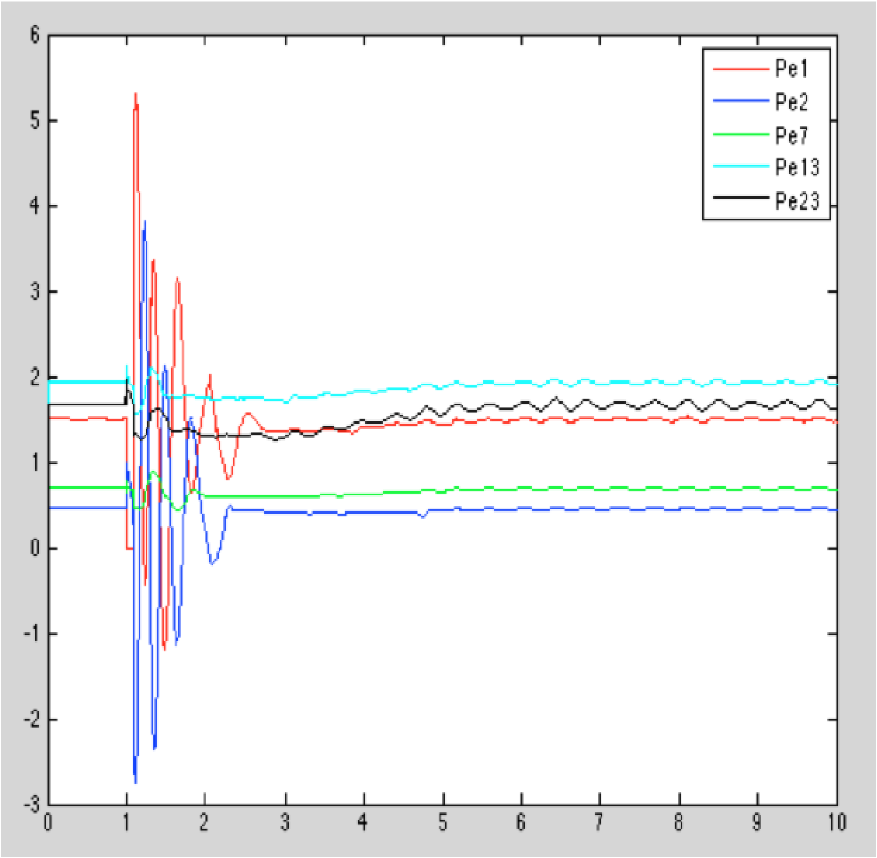
Response with critical generators meeting the standard

Note: Hard to map system level standards to "critical" components; all must participate

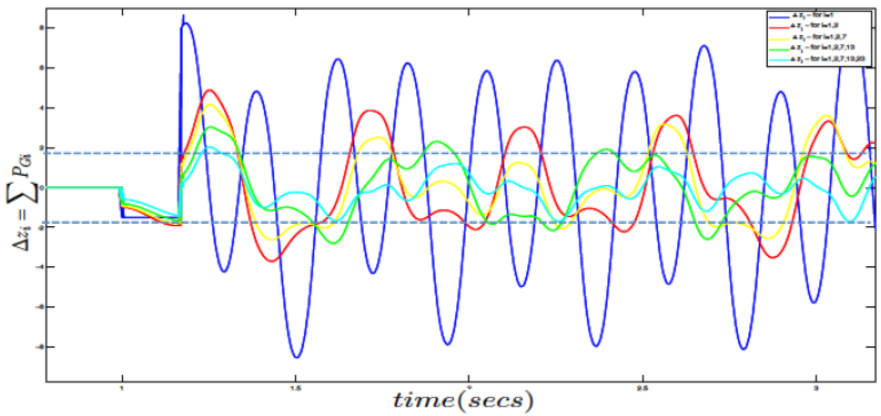


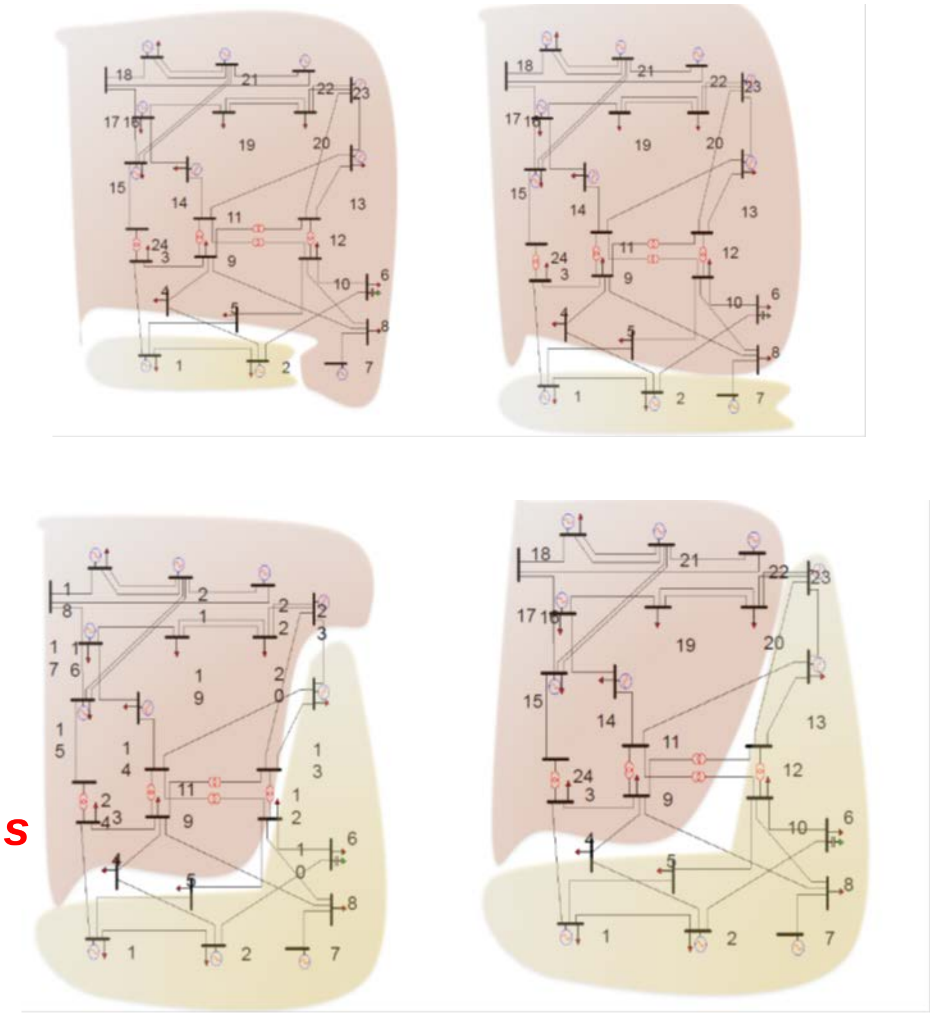
Power output deviations with or w/o meeting dynamic standard by critical components





Int-V based bottom-up aggregation for cooperation





$$z_k = \sum_{i=1}^{k} P_{g,i}$$

Dynamic standard gives bounds on iBAs

S.Baros, M.Ilic intelligent Balancing Authorities (iBAs) for Transient Stabilization of Large Power Systems IEEE PES General Meeting 2014

Our proposed dynamic standard design

- Every (group) of components within an electrically interconnected system must meet a set of dynamic standards (shown in Table 1)
- Formation of groups (iBAs) within today's control areas is communicated to the next higher standards authority to which the group belongs. This forms "nested" hierarchies—uniquely defined by identifying the electrical neighbors. We refer to these as general intelligent Balancing Authorities (iBAs).
- Each iBA must meet family of dynamic standards defined in terms of bounds on energy and power deviation ranges from schedules.

Conclusions and open questions

- Fundamental need for family of dynamic standards
- Structure-based multi-layered/multi-temporal modeling is the basis for capturing dynamic interactions
- Standard specifications a natural evolution from the existing AGC standards (extensions to dynamics, inclusion of voltage, modular)
- Basis for innovation (deployment of "smarts") at value
- Proposed one possible approach to design these
- Recommend working with industry (NERC, FERC)

Thank you!

Contact info:

Marija Ilic (milic@ece.cmu.edu)