Toward IT-Enabled Power Systems: Large-scale distributed control for tomorrow's electricity grid

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Outline

- **Technological and social drivers in the electric energy systems**
- **Examples of what we can do**
- **Examples of what we cannot do (yet)**
- Major challenge and opportunity for distributed control and estimation
- The key questions: Unique structure of complex electric energy systems and implications on what can be done in a distributed way and what cannot
- Possibility of plug-and-play standards for system dynamics?
- The challenge of innovation

Technological and social drivers in the electric energy systems

- Multiple objectives (reliability, efficiency and environmental)
- Portfolia of non-utility-owned resources
- Renewable resources and demand response
- Technology drivers: Cost-effective IT; GPS synchronized wide-area measurement systems (WAMS)
- Emergence of electricity markets
- Technologies for plug-and-play deployment

An illustrative future electric grid [21]

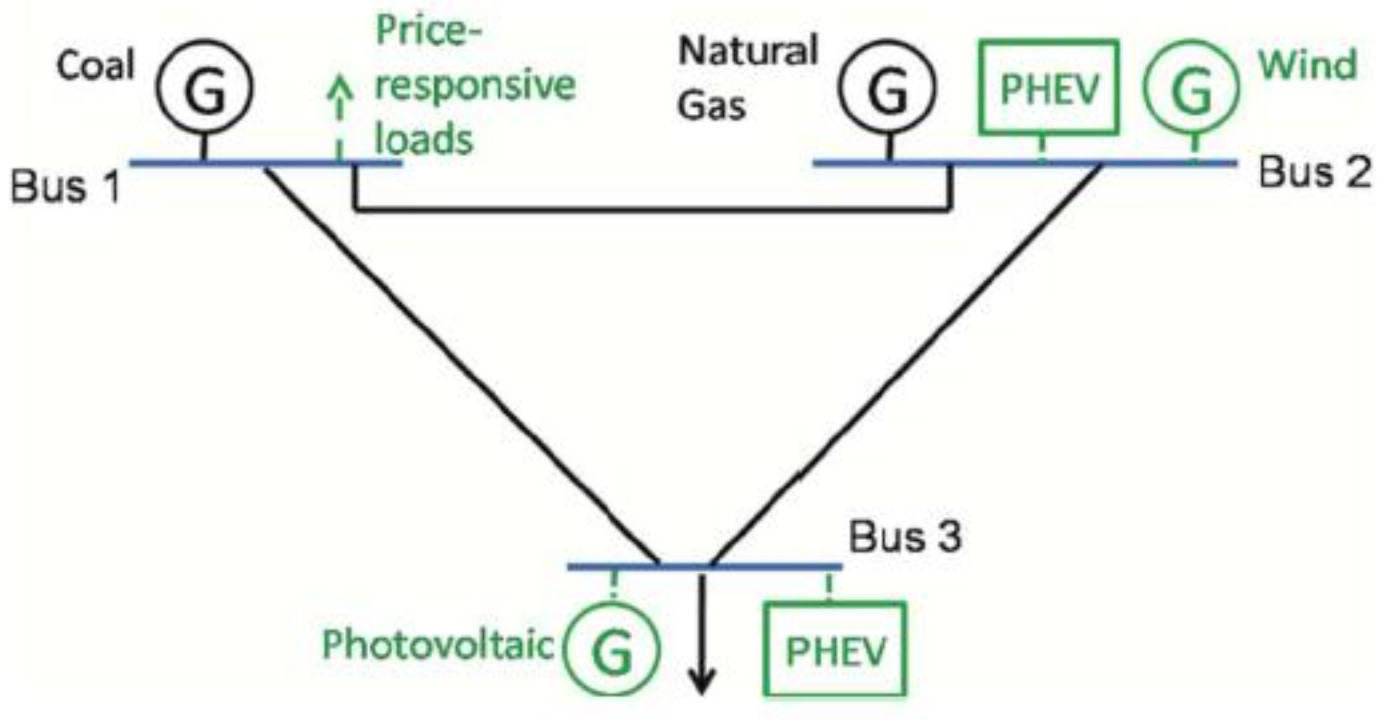
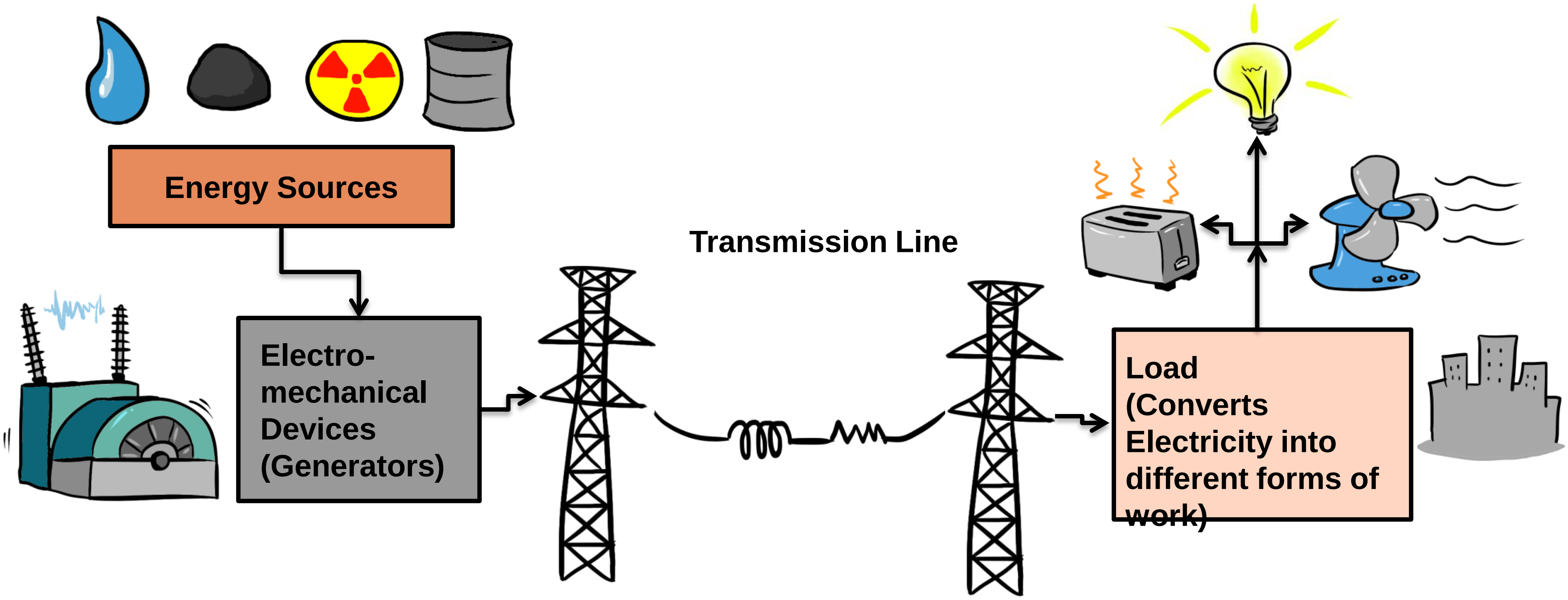


Fig. 5. Small example of the future electric energy system.

Conventional Power System



Energy Sources

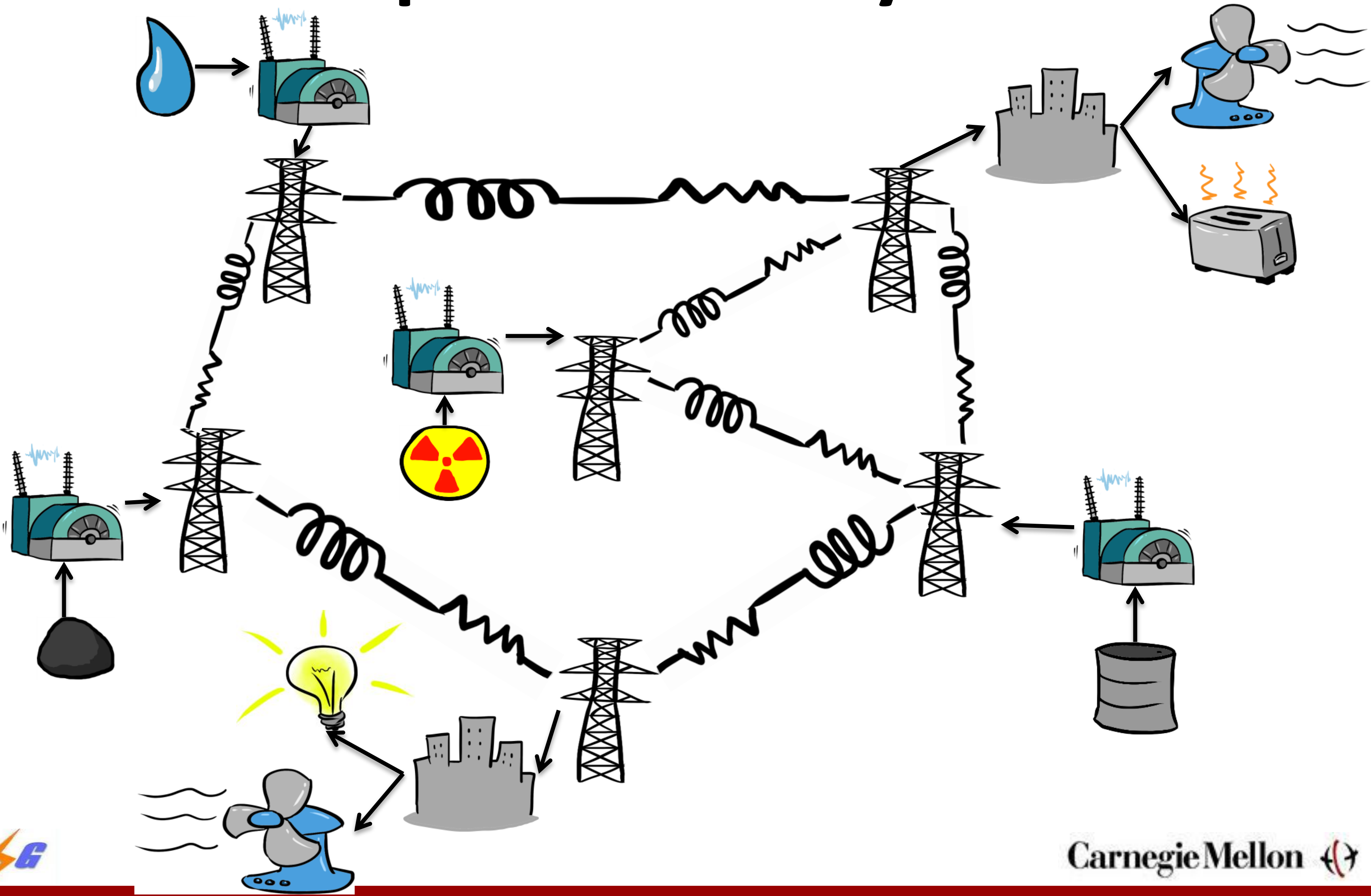
Electro-
mechanical
Devices
(Generators)

Transmission Line

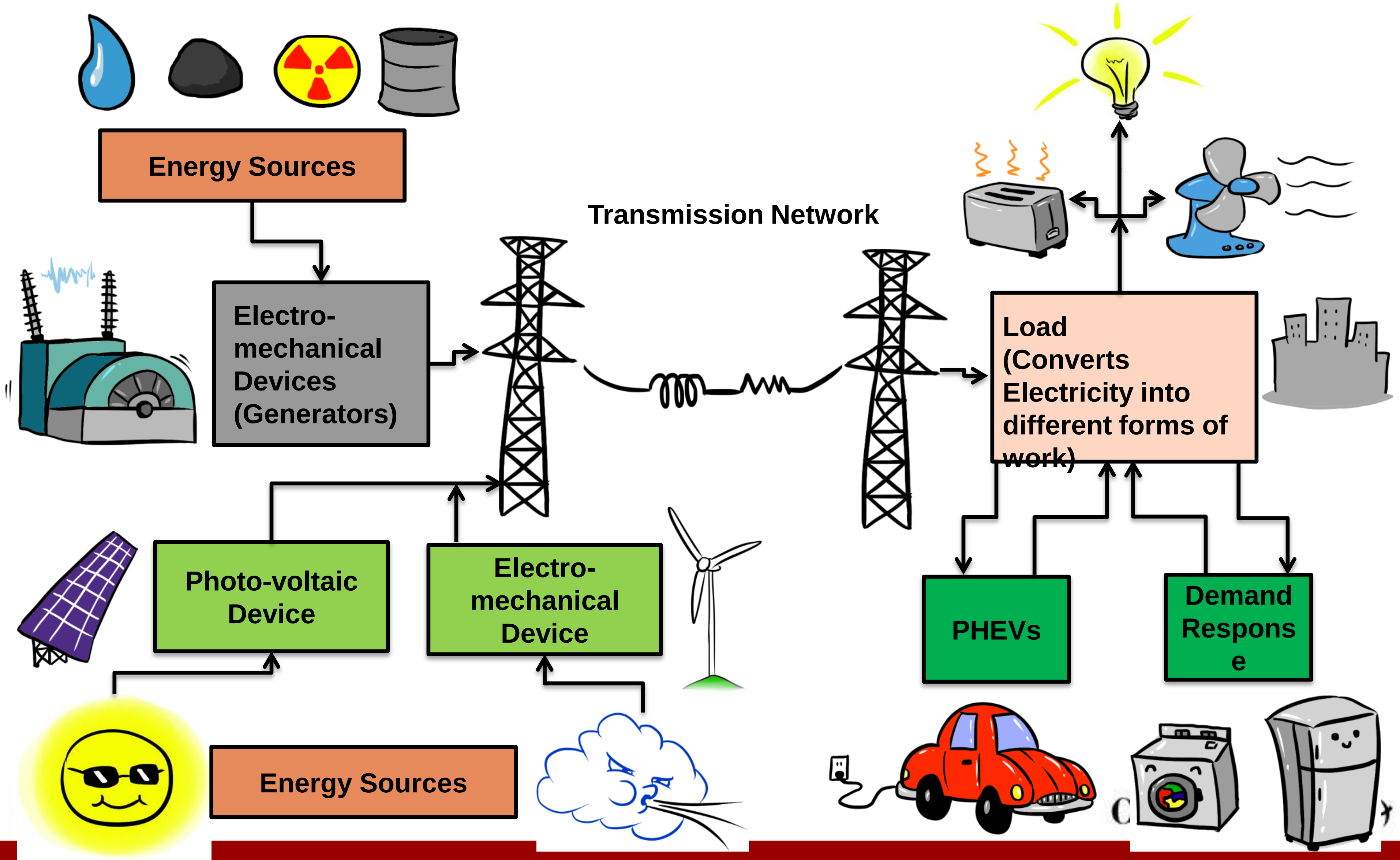
Load
(Converts
Electricity into
different forms of
work)

The next four slides drawn by Andrew Hsu.

More Complex Power System



Future Power Systems



Energy Sources

Electro-mechanical Devices (Generators)

Transmission Network

Load (Converts Electricity into different forms of work)

Photo-voltaic Device

Electro-mechanical Device

PHEVs

Demand Response

Energy Sources

Potential Use of Real-Time Measurements for Data-Driven Control and Decision-Making (new)

- GPS synchronized measurements (synchrophasors ; power measurements at the customer side.
- The key role of off-line and on-line computing. Too complex to manage relevant interactions using models and software currently used for planning and operations.
- Our proposed design: Dynamic Monitoring and Decision Systems (DYMONDS)

New technical problem

- At present the physical energy system, including its communications and control, does not readily enable choice and multi-participant information exchange and processing for aligning often conflicting goals.
- It is essential to design intelligence for T&D operations to align these goals and consequently to make the most out of available resources while simultaneously offering robust and affordable quality of service.
- New flexible energy processing equipment will also be needed to handle increased variety and bandwidth of many participant requests.

The Changing Role of Decision Making

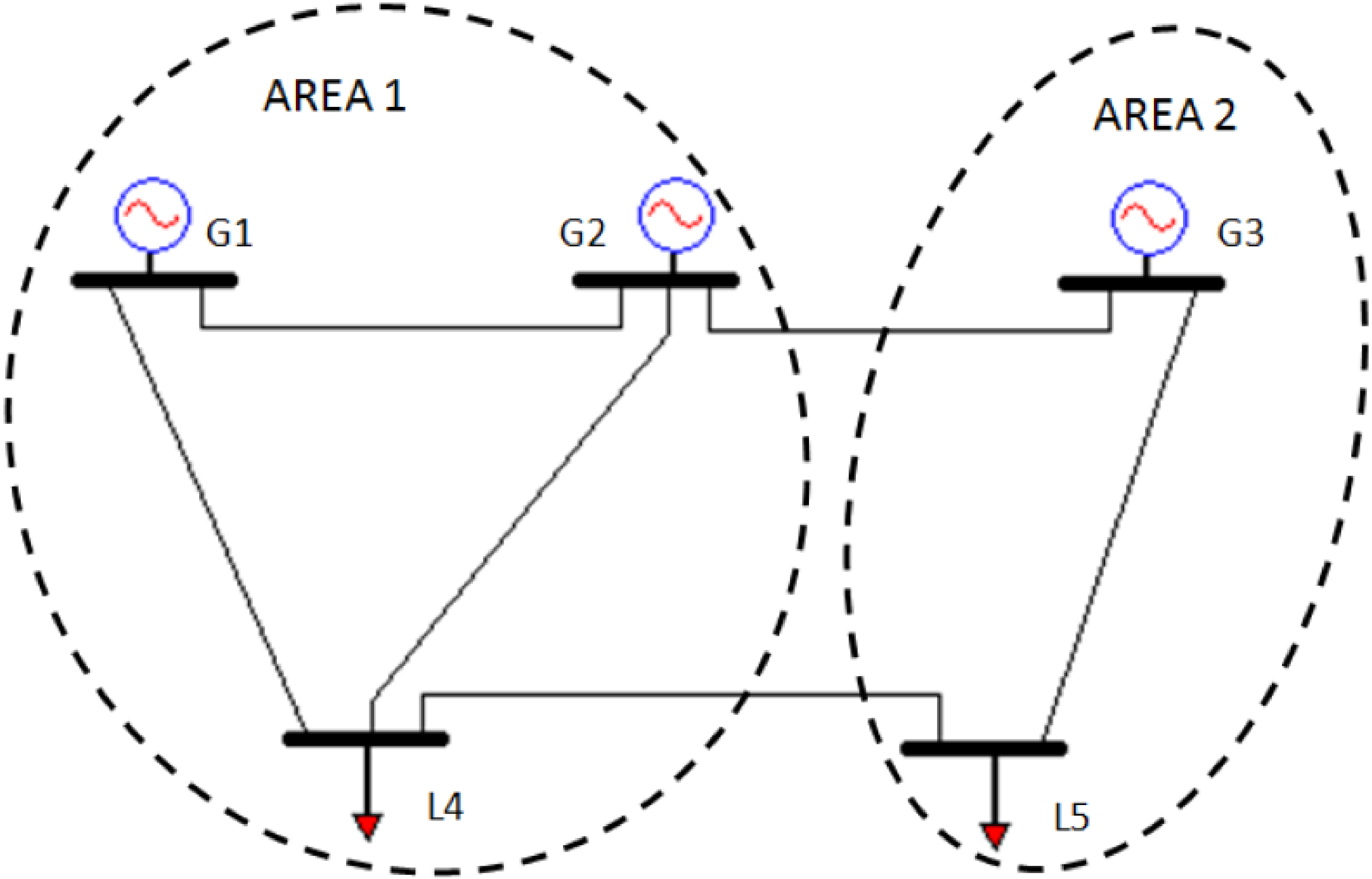
Today's Decision Making	Tomorrow's Decision Making
Deliver supply to meet given demand	Deliver power to support supply and demand schedules in which both supply and demand have costs assigned
Deliver power assuming a predefined tariff	Deliver electricity at QoS determined by the customers willingness to pay
Deliver power subject to predefined CO_2 constraint	Deliver power defined by users' willingness to pay for CO_2
Deliver supply and demand subject to transmission congestion	Schedule supply, demand and transmission capacity (supply, demand and transmission costs assigned); transmission at value
Use storage to balance fast varying supply and demand	Build storage according to customers willingness to pay for being connected to a stable grid
Build new transmission lines for forecast demand	Build new transmission lines to serve customers according to their ex ante (longer-term) contracts for service

Difficult Questions:
Systematic ICT Design for Energy Systems

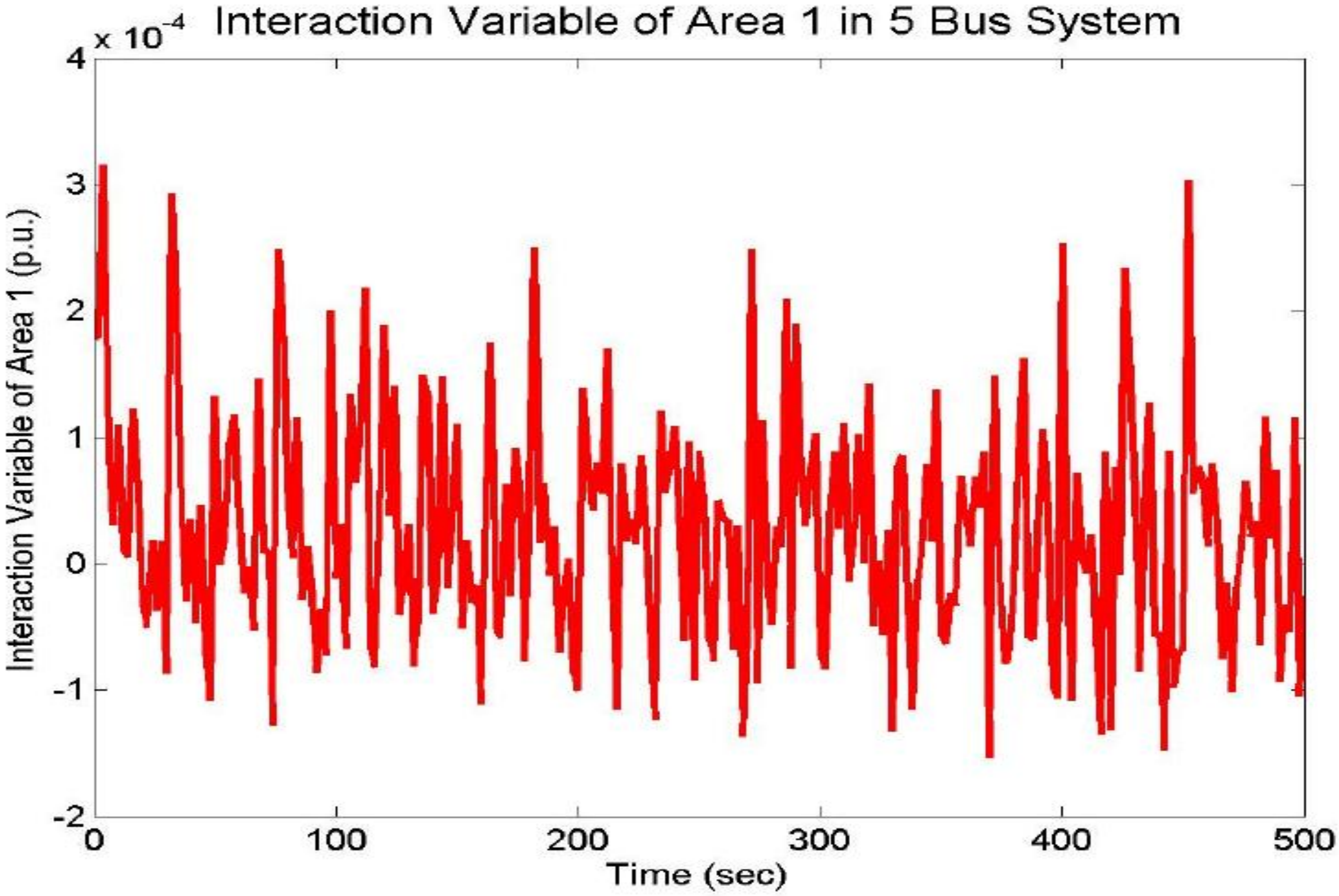
- Establish sufficiently accurate (but not too complex) modeling framework which captures inter-dependencies of energy Socio-Ecological Systems (SES), physical grid, ICT and governance system
- The key objective: Match attributes of energy SES, physical grid, ICT and governance system by designing around a given energy SES
- Interaction variables: A means of going from very coarse to granular and back
- ICT design to manage interaction variables (temporal, spatial and contextual)
- Interaction variables-based unifying framework for relating engineering design, financial and environmental objectives

Vast temporal and spatial scales-engineering view

Interaction Variable Simulation for Real Power Problem in 5 Bus System



Vast temporal and spatial inter-dependencies (deeper-level)



Interaction variables within a physical system

- Interaction variables --- variables associated with sub-systems which can only be affected by interactions with the other sub-systems and not by the actions taken at the sub-system level
- Dynamics of physical interaction variables zero when the system is disconnected from other sub-systems

Coarse modeling of Socio-Ecological Systems (using SES interaction variables) [16]

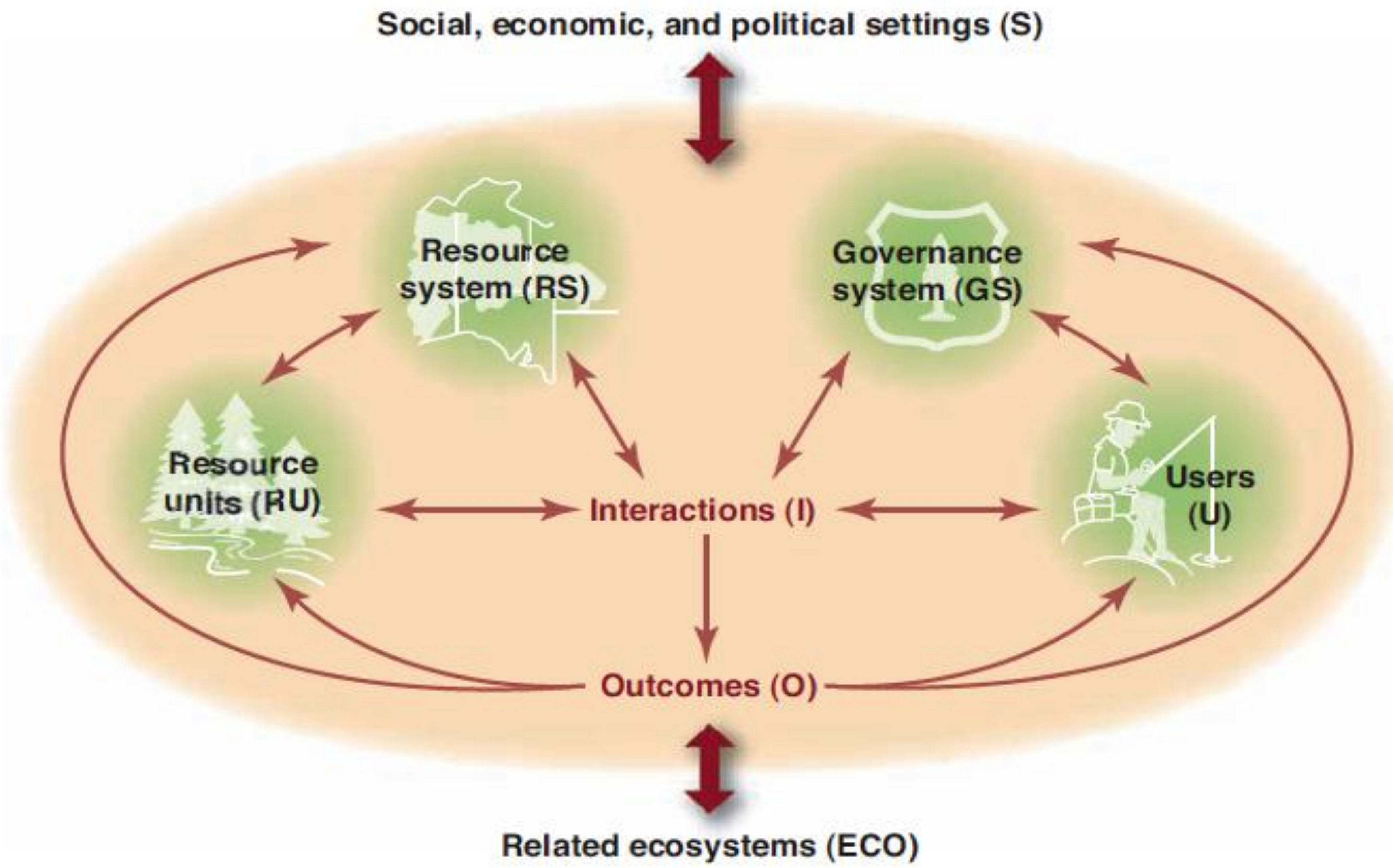


Fig. 1. The core subsystems in a framework for analyzing social-ecological systems.

“Smart Grid” ←→ electric power grid and ICT for sustainable energy SES [14]

Energy SES

- Resource system (RS)
- Generation (RUs)
- Electric Energy Users (Us)

Man-made Grid

- Physical network connecting energy generation and consumers
- Needed to implement interactions

Man-made ICT

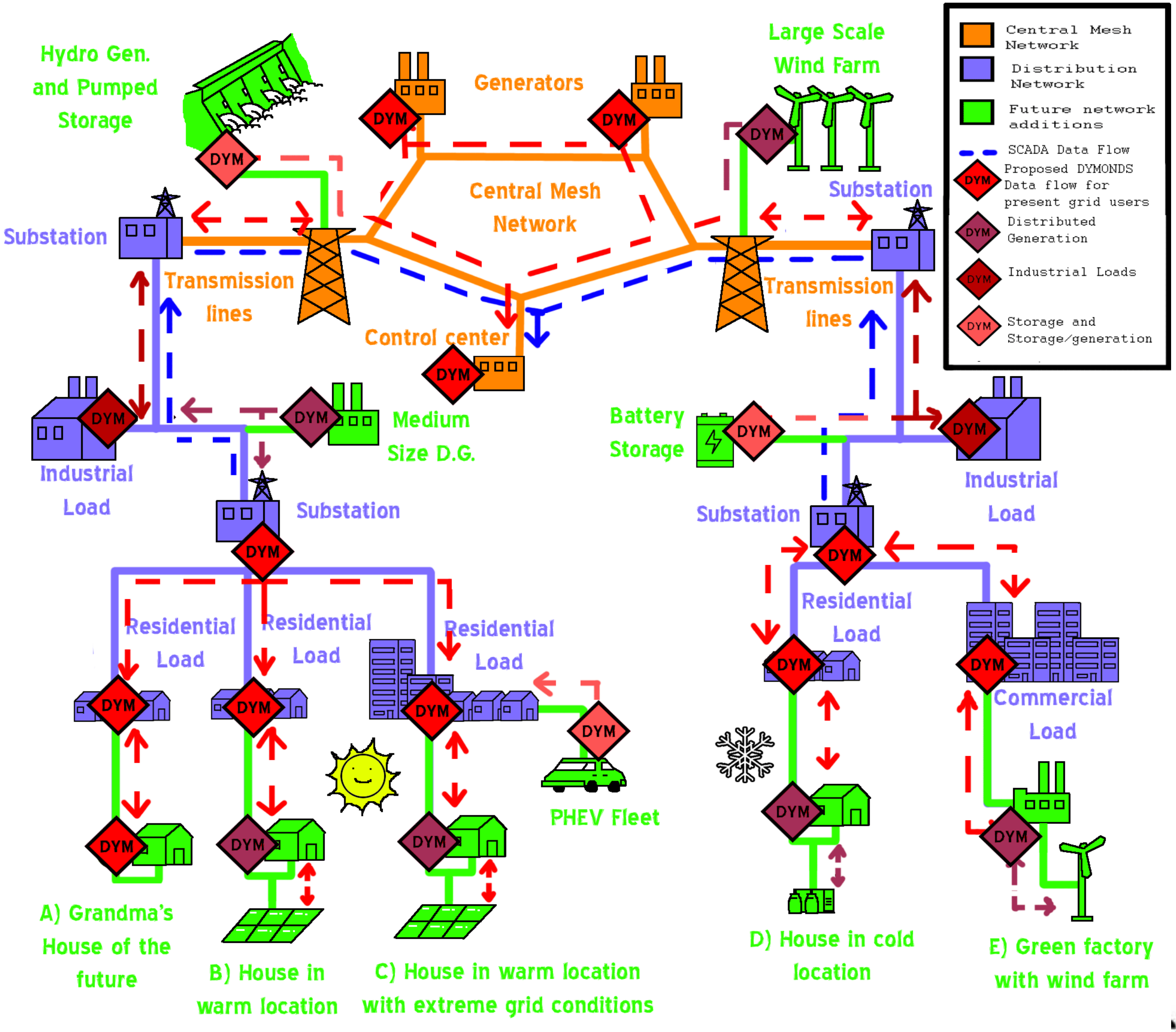
- Sensors
- Communications
- Operations
- Decisions and control
- Protection
- Needed to align interactions

ICT Design for New Architectures

- **Measuring, communicating and controlling (physical) grid interaction variables to shape the deeper-level interaction variables of SES systems to induce sustainable performance**

- The creation of “smart grids” is the application of information technology to the power system while coupling this with an understanding of the business and regulatory environment
- Critical to the creation of “smart grids” is;
  - development of models of the power system
  - development of control software
  - incorporation of security, communications, and safety systems

DYMONDS-enabled Physical Grid [14]



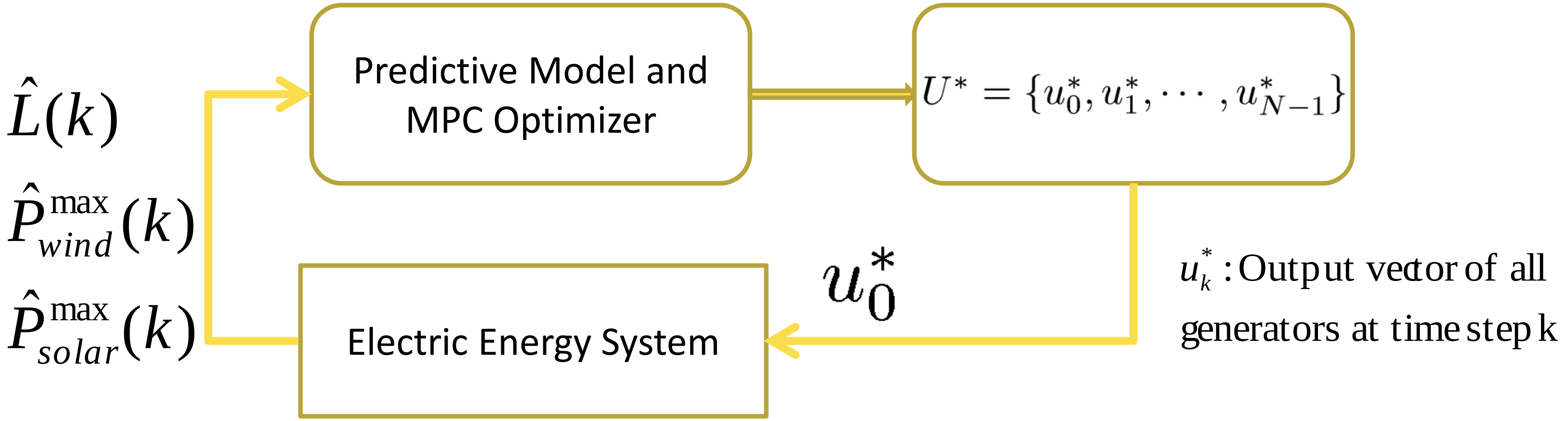
New challenge and opportunity for control, communications and control: What can be done in a distributed way

- Balance forecast supply and demand in systems with intermittent resources- scheduling problem
- Multi-temporal approximations of multi-stage scheduling under uncertainties
- Multi-layered approximations of large networks (decomposition, aggregation)
- Proof-of-concept simulations using real-world data for Azores Islands
- Hierarchical assumptions may not hold

Basic idea of minimally coordinated self-dispatch—DYMONDS

- Distributed management of temporal interactions
- Different technologies perform look-ahead decision making given their unique temporal and spatial characteristics and system signal (price or system net demand); they create bids and are cleared by the layers of coordinators
- Putting Auctions to Work in Future Energy Systems
- We illustrate next a supply-demand balancing process in an energy system with wind, solar, conventional generation, elastic demand, and PHEVs.

Centralized MPC –Benchmark



$\hat{L}(k)$

$\hat{P}_{wind}^{\max}(k)$

$\hat{P}_{solar}^{\max}(k)$

Predictive Model and MPC Optimizer

$U^* = \{u_0^*, u_1^*, \cdots, u_{N-1}^*\}$

Electric Energy System

u_0^*

u_k^* : Output vector of all generators at time step k

- Predictive models of load and intermittent resources are necessary.
- Optimization objective: minimize the total generation cost.
- Horizon: 24 hours, with each step of 5 minutes.

Problem 3A: Centralized MPC-based Dispatch with Inelastic Demand

$$\text{Solve}: \min_{P_G} \sum_{k=1}^{K} \sum_{i \in G} (C_i(P_{G_i}(k))), i \in G \tag{39}$$

$$s.t. \sum_{i} P_{G_i}(k) = \sum_{z} \hat{L}_z(k), i \in G, z \in Z; \tag{40}$$

$$\hat{L}_z(k) = f_z(L_z(k-1)), z \in Z; \tag{41}$$

$$\hat{P}_{G_j}^{max}(k) = g_j(\hat{P}_{G_j}^{max}(k-1)); \tag{42}$$

$$\hat{P}_{G_j}^{min}(k) = h_j(\hat{P}_{G_j}^{min}(k-1)); \tag{43}$$

$$\hat{P}_{G_j}^{\mathrm{min}} \leq P_{G_j}(k) \leq \hat{P}_{G_j}^{\mathrm{max}}, j \in G_r; \tag{44}$$

$$P_{G_i}^{\mathrm{min}} \leq P_{G_i}(k) \leq P_{G_i}^{\mathrm{max}}, i \in G \setminus G_r; \tag{45}$$

$$|P_{G_i}(k+1) - P_{G_i}(k)| \leq R_i, i \in G; and, \tag{46}$$

$$|F(k)| \leq F^{max}. \tag{47}$$

Problem 3B: Centralized MPC-Based Dispatch with Elastic Load

$$\text{Solve}: \min_{P_G, L} \sum_{k=1}^{K} \left(\sum_{i \in G} (C_i(P_{G_i}(k))) - \sum_{z \in Z} (B_z(L_z(k))) \right), \tag{48}$$

$$s.t. \sum_{i \in G} P_{G_i}(k) = \sum_{z \in Z} L_z(k); \tag{49}$$

$$\hat{P}_{G_r}^{max}(k) = g_j(\hat{P}_{G_r}^{max}(k-1)), r \in G_r; \tag{50}$$

$$\hat{P}_{G_r}^{min}(k) = g_j(\hat{P}_{G_r}^{min}(k-1)), r \in G_r; \tag{51}$$

$$\hat{P}_{G_j}^{\min} \leq P_{G_j}(k) \leq \hat{P}_{G_j}^{\max}, j \in G_r; \tag{52}$$

$$P_{G_i}^{\min} \leq P_{G_i}(k) \leq P_{G_i}^{\max}, i \in G \setminus G_r; \tag{53}$$

$$|P_{G_i}(k+1) - P_{G_i}(k)| \leq R_i, i \in G; and, \tag{54}$$

$$|F(k)| \leq F^{max}. \tag{55}$$

DYMONDS for MPC-based supply function computation-

Given:

$$[\hat{\lambda}(k+1) \quad \hat{\lambda}(k+2) \quad \cdots \quad \hat{\lambda}(k+K)]$$

$$\text{Solve:} \quad \max_{P_{G_i}(k)} \sum_{k+1}^{k+K} \lambda(\hat{k})(P_{G_i}(k)) - (C_i(P_{G_i}(k))) \tag{44}$$

$$\text{s.t.} \quad \hat{P}_{G_i}^{\max}(k) = g_i(\hat{P}_{G_i}^{\max}(k-1)) \tag{45}$$

$$\hat{P}_{G_i}^{\min}(k) = h_i(\hat{P}_{G_i}^{\min}(k-1)) \tag{46}$$

$$|P_{G_i}(k+1) - P_{G_i}(k)| \leq R_i \text{ and} \tag{47}$$

$$\hat{P}_{G_i}^{\min} \leq P_{G_i}(k) \leq \hat{P}_{G_i}^{\max}. \tag{48}$$

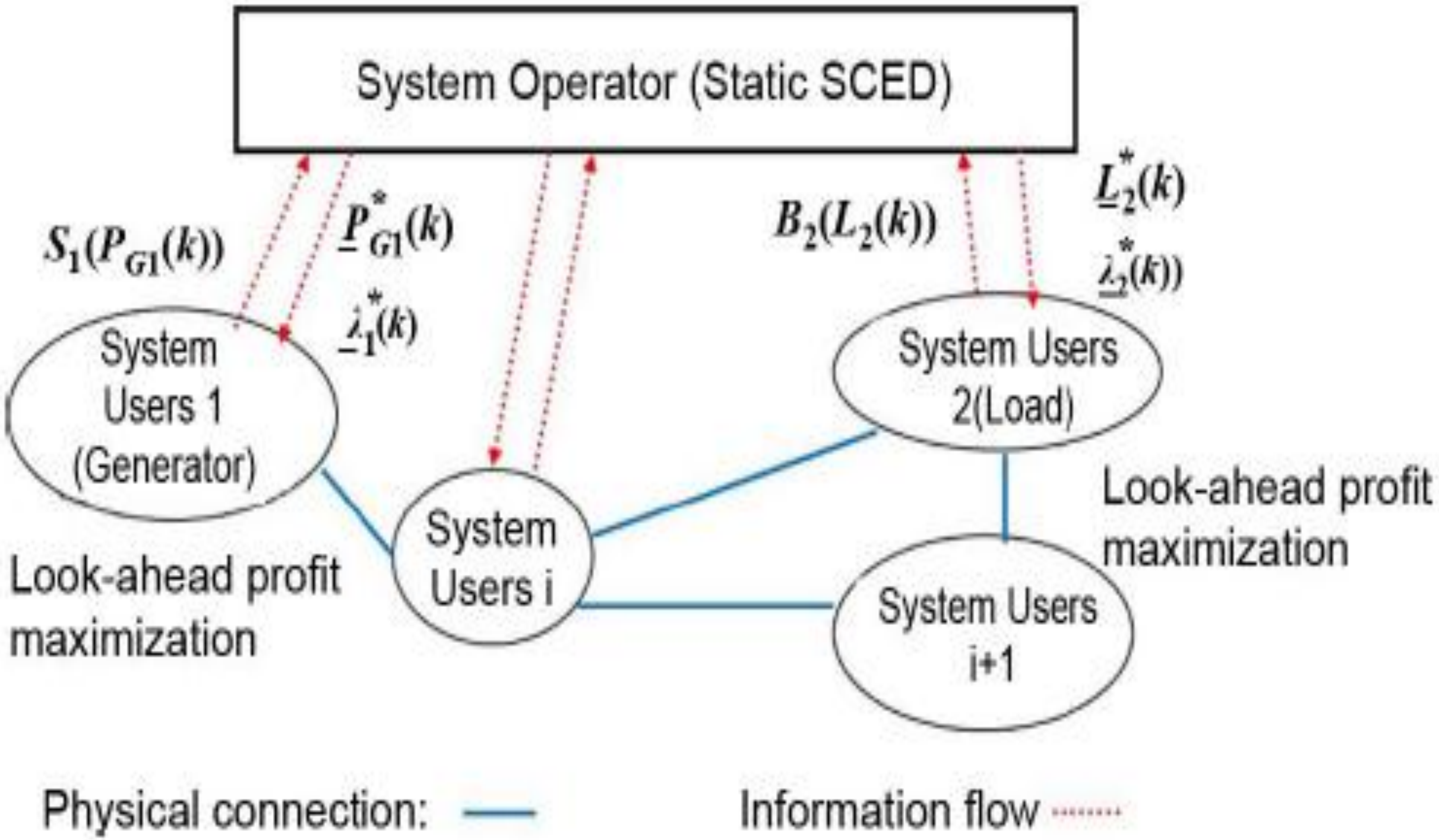
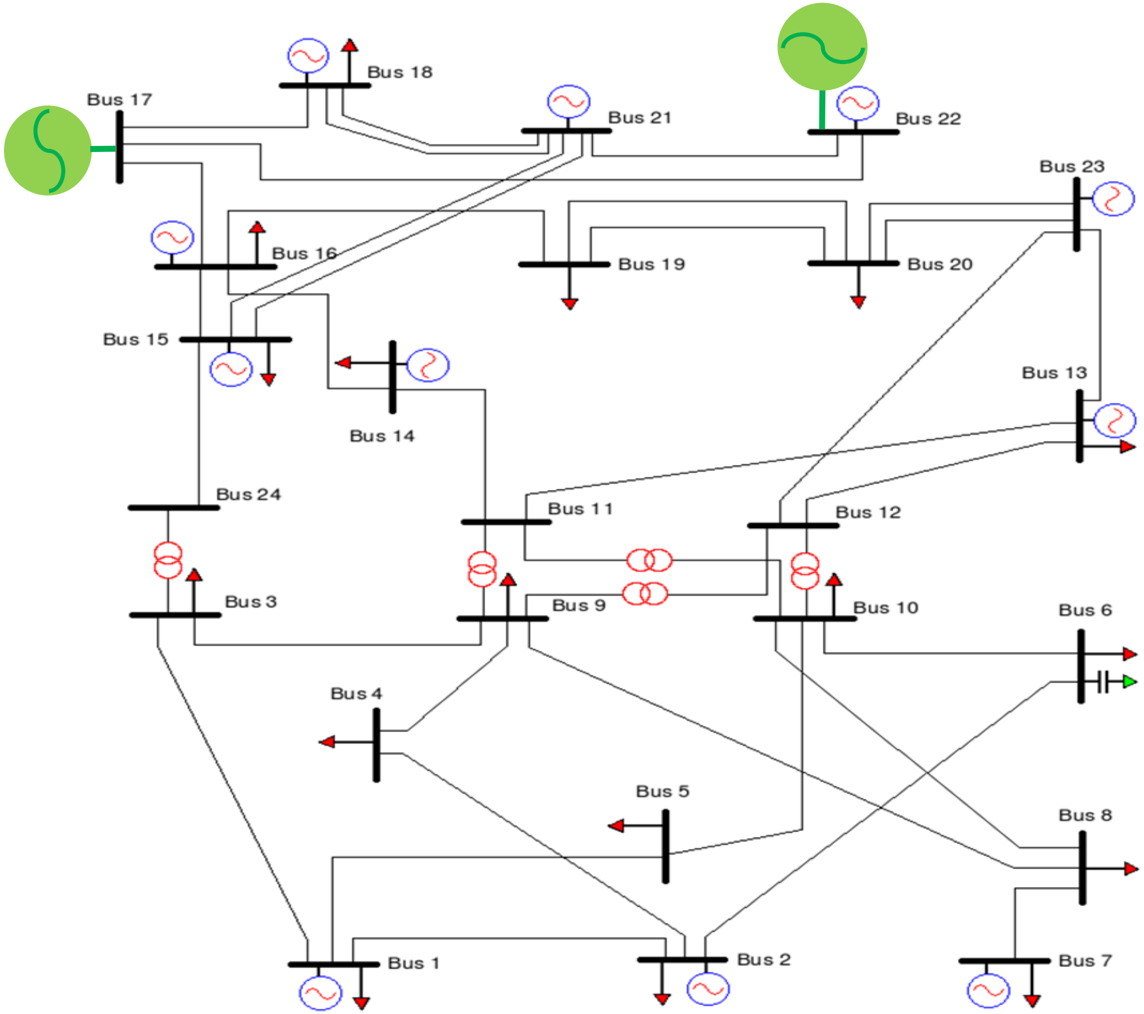
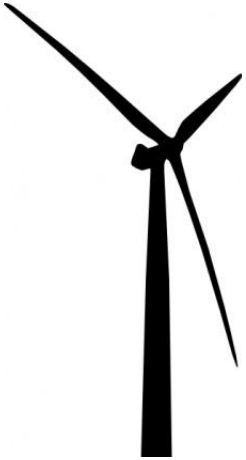


Fig. 3. Required information exchange for DYMONDS-based dispatch.

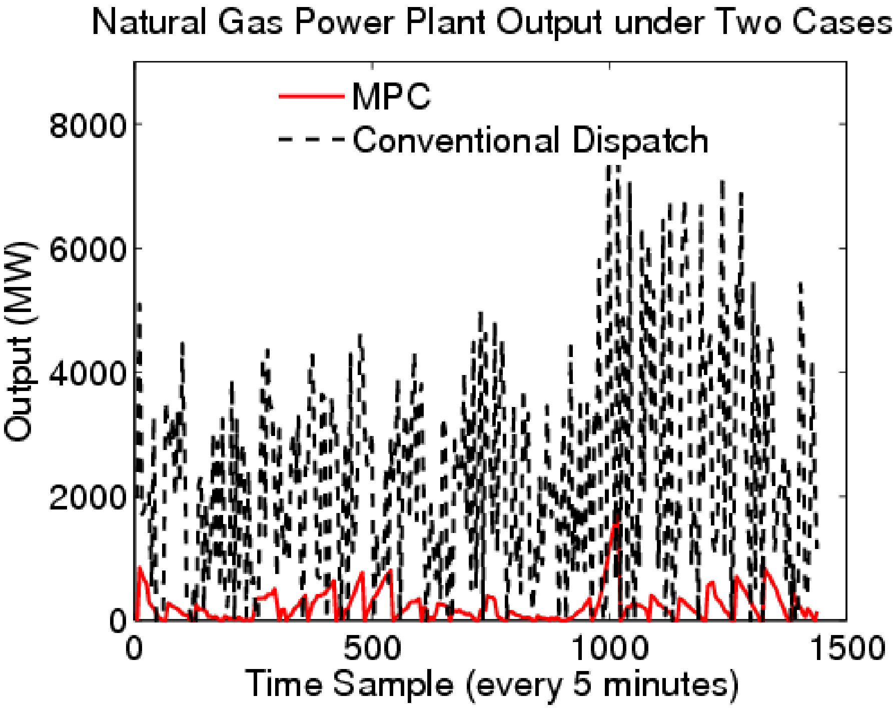
DYMONDS Simulator
IEEE RTS with Wind Power

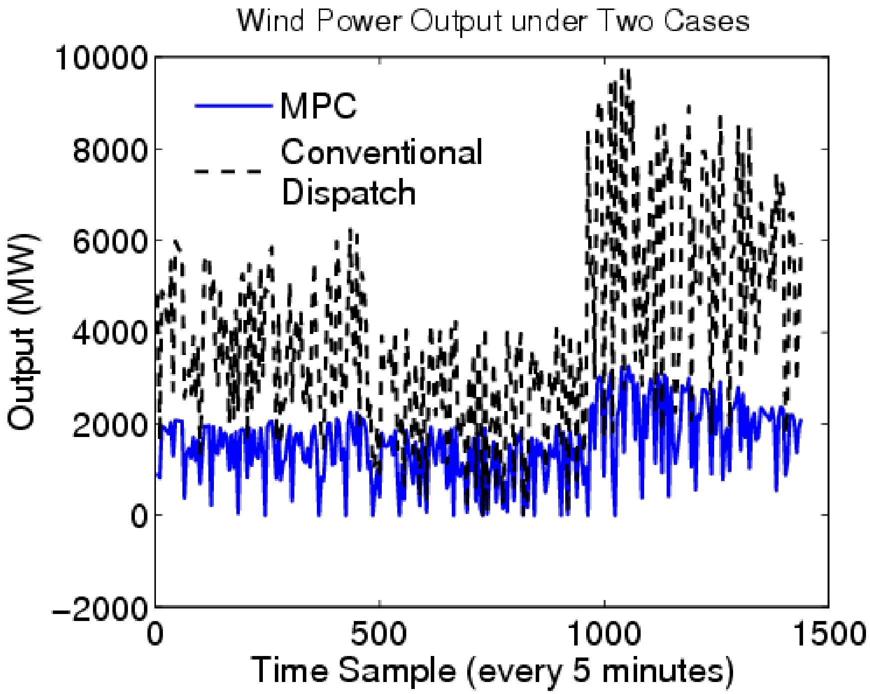




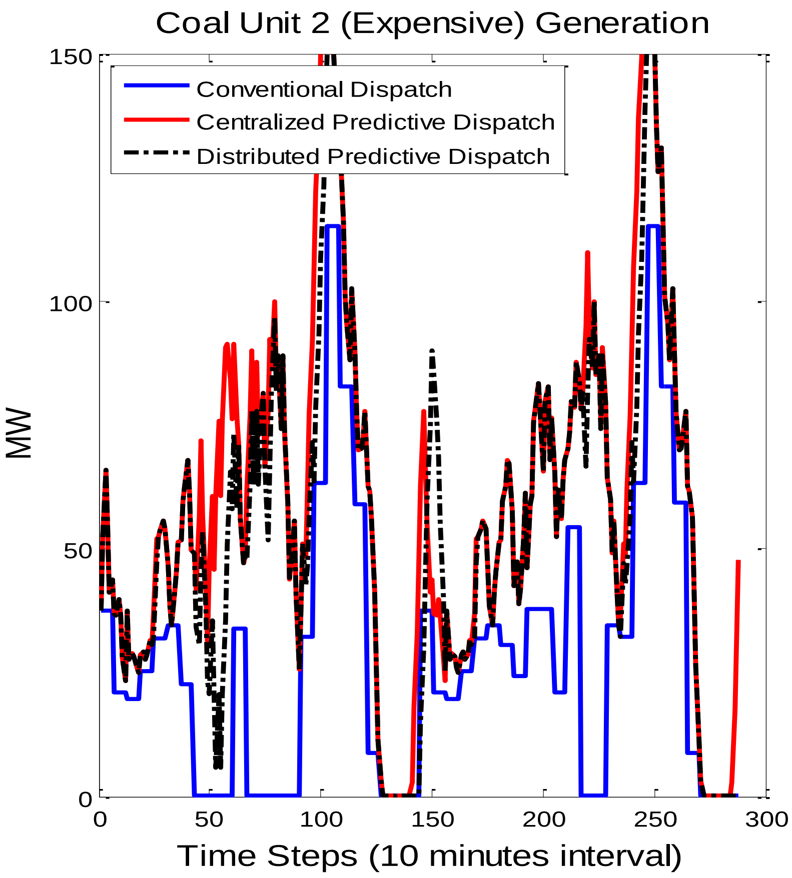
- 20% / 50% penetration to the system [2]

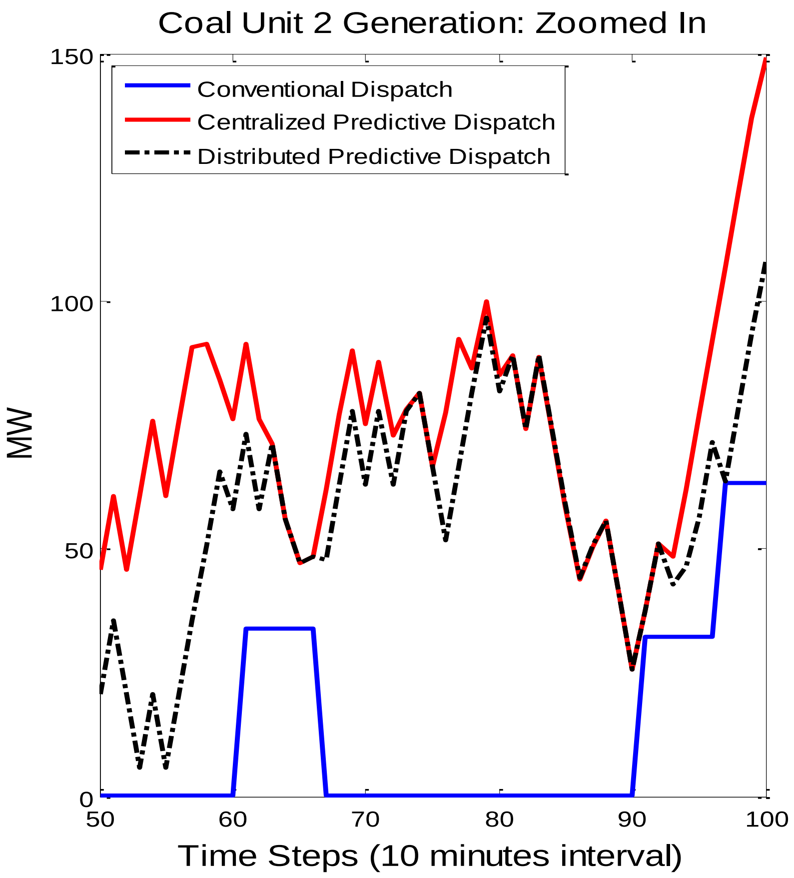
Conventional cost over 1 year *	**Proposed cost over the year**	**Difference**	**Relative Saving**
$ 129.74 Million	$ 119.62 Million	$ 10.12 Million	7.8%





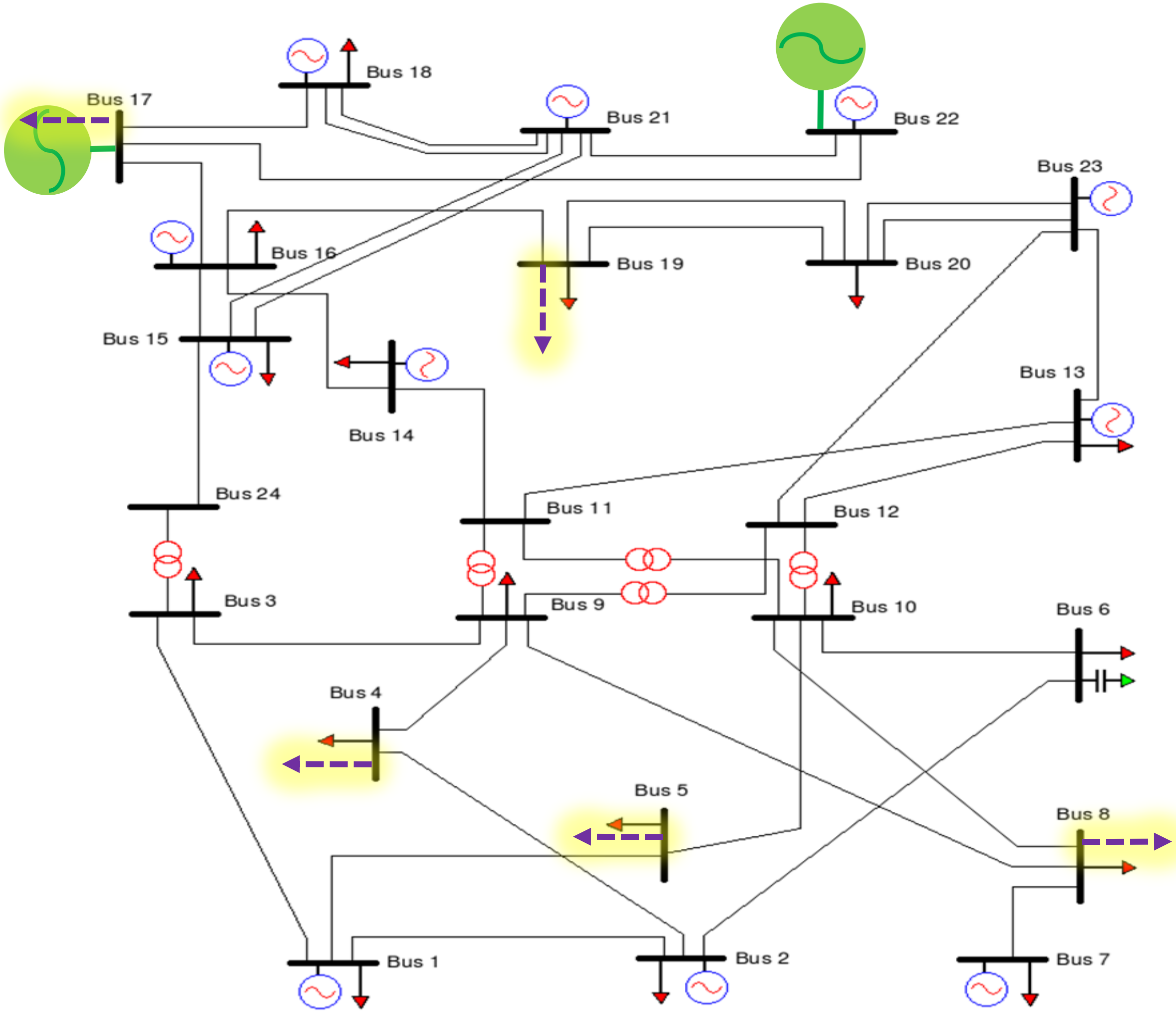
*: load data from New York Independent System Operator, available online at: http://www.nyiso.com/public/market_data/load_data.jsp

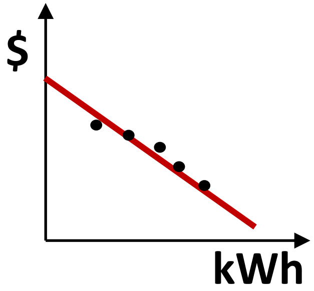

Coal Unit 2 (Expensive) Generation


Coal Unit 2 Generation: Zoomed In

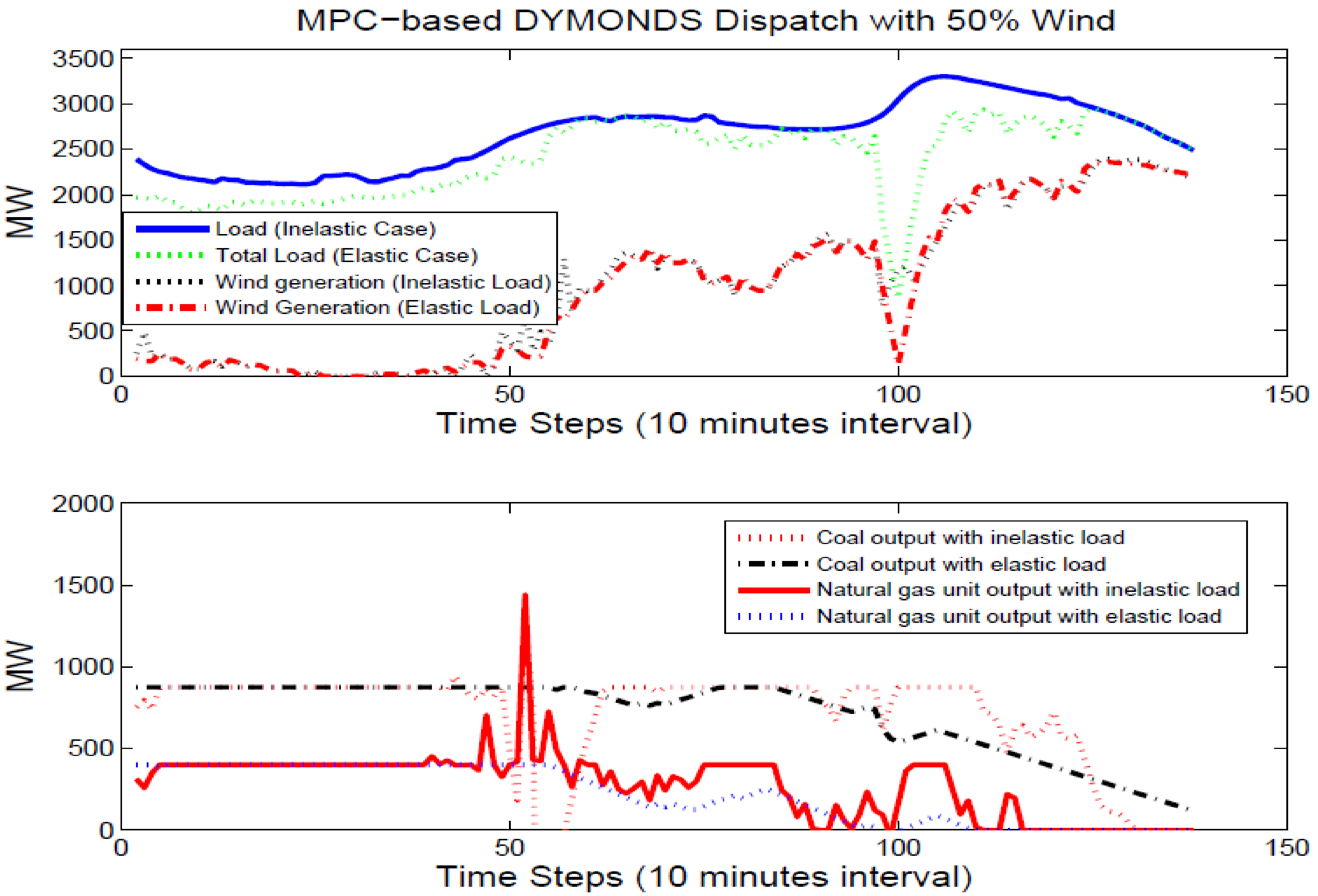
BOTH EFFICIENCY AND RELIABILITY MET

DYMONDS Simulator
Impact of price-responsive demand

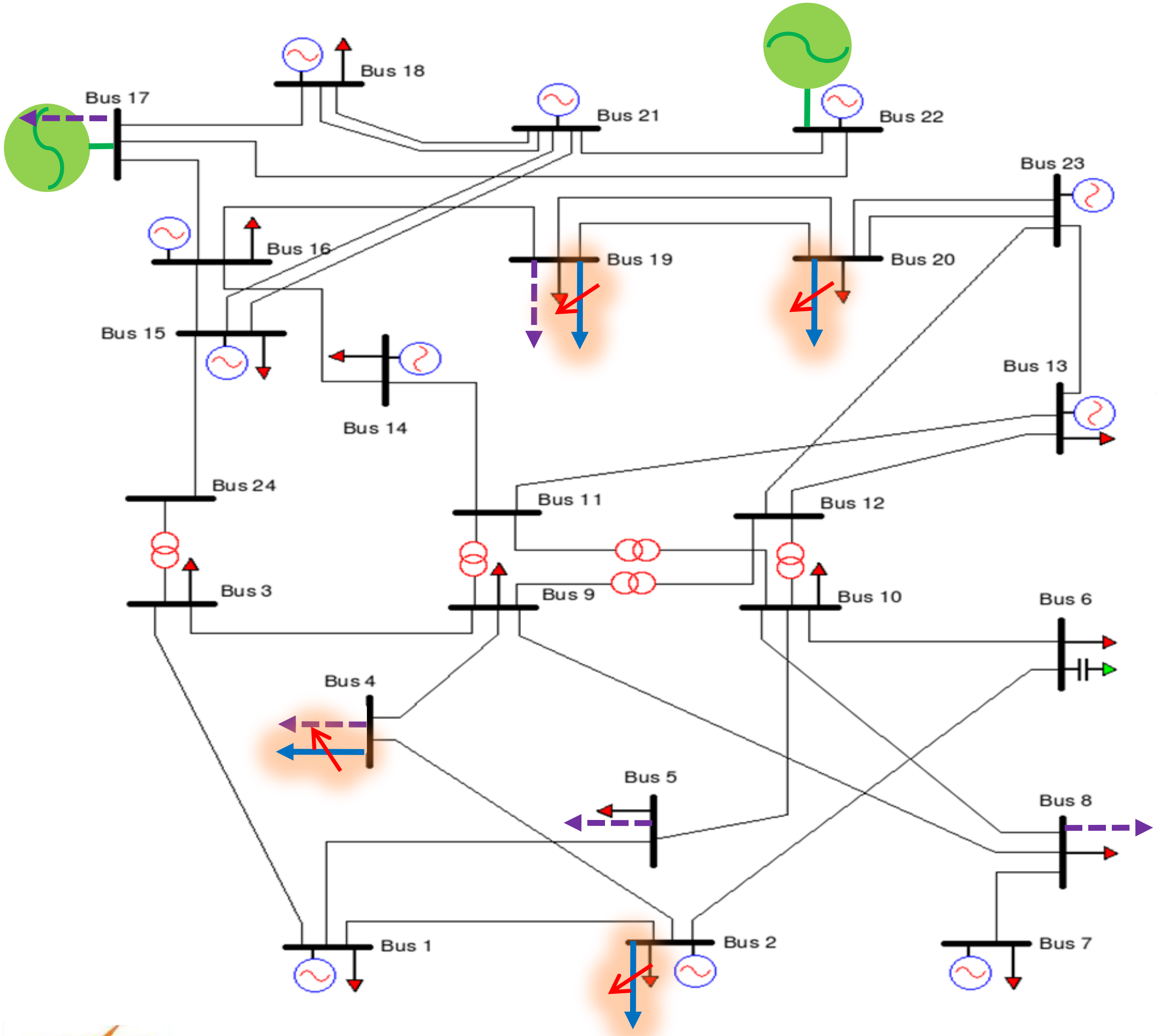




- Elastic demand that responds to time-varying prices

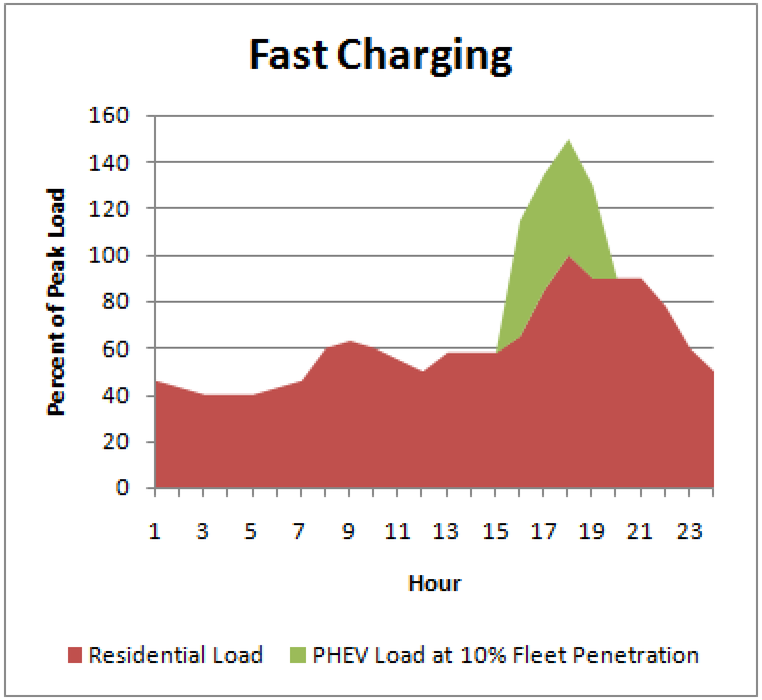

MPC−based DYMONDS Dispatch with 50% Wind
MW
3500
3000
2500
2000
1500
1000
500
0
Load (Inelastic Case)
Total Load (Elastic Case)
Wind generation (Inelastic Load)
Wind Generation (Elastic Load)
0
50
100
150
Time Steps (10 minutes interval)
MW
2000
1500
1000
500
0
Coal output with inelastic load
Coal output with elastic load
Natural gas unit output with inelastic load
Natural gas unit output with elastic load
0
50
100
150
Time Steps (10 minutes interval)

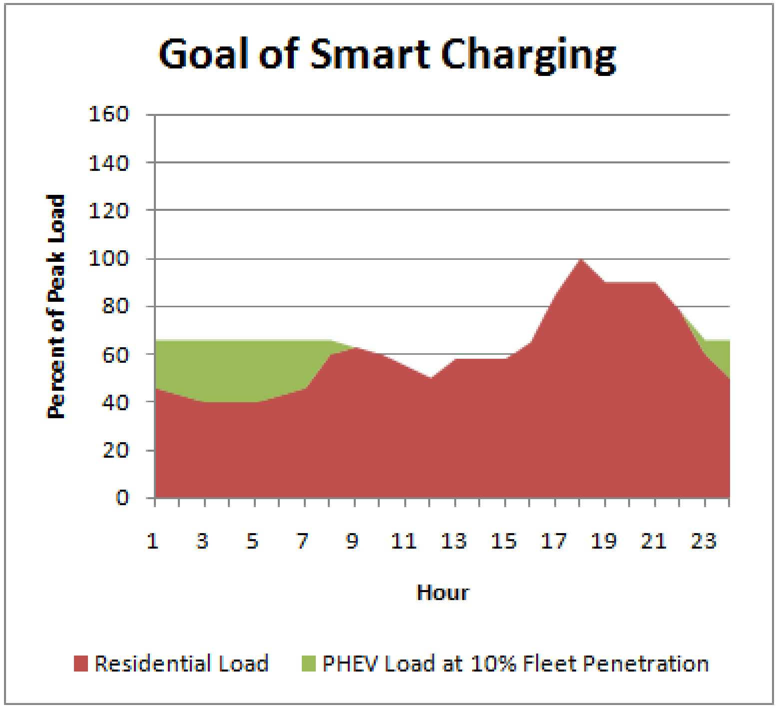
DYMONDS Simulator
Impact of Electric vehicles

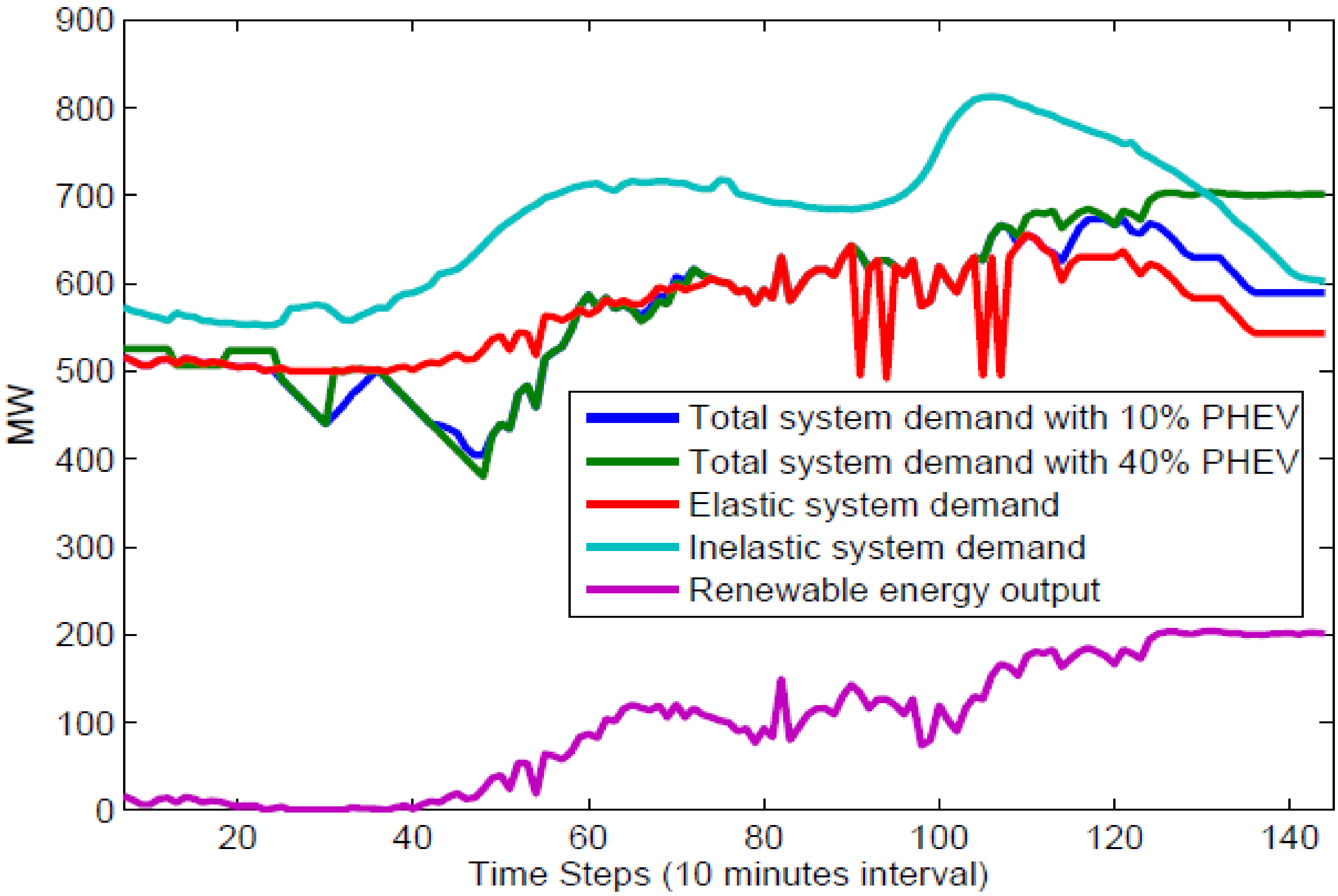


- Interchange supply / demand mode by time-varying prices

Optimal Control of Plug-in-Electric Vehicles: Fast vs. Smart





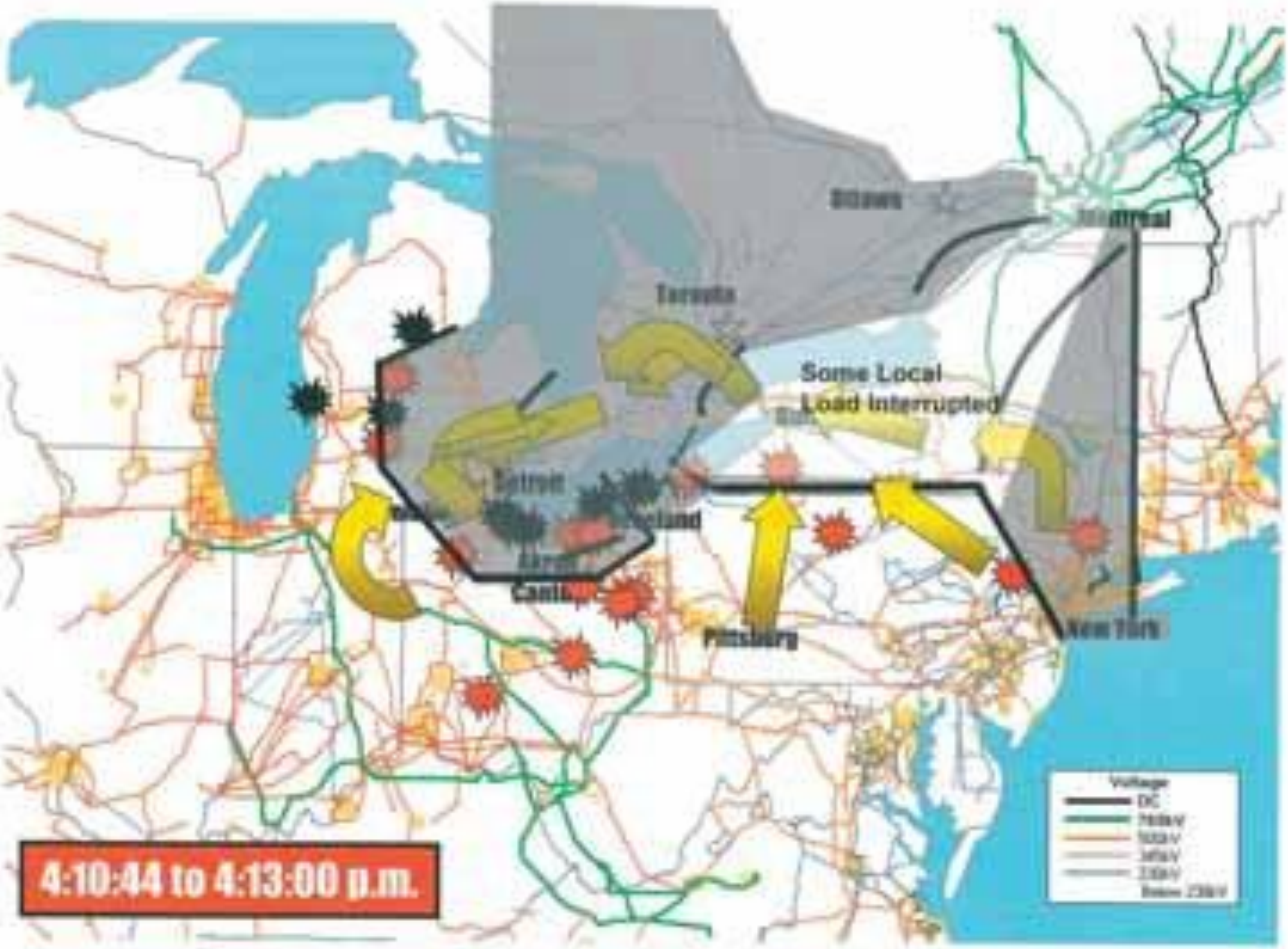


900
800
700
600
500
400
300
200
100
0
MW
20
40
60
80
100
120
140
Time Steps (10 minutes interval)
Total system demand with 10% PHEV
Total system demand with 40% PHEV
Elastic system demand
Inelastic system demand
Renewable energy output

Examples of what we cannot do (yet)

- **Optimal power transfers**
- Corrective resource management, including adaptive voltage support

  -nonlinear AC power flows
- Efficient stabilization and regulation in response to deviations from forecast
- Efficient management of reserves; major challenge[25]
- Central generation vs. distributed energy resources (DERs)
- Dependence of reserve requirements on standards for dynamics
-



4:10:44 to 4:13:00 p.m.

Alleviate Interface Congestion

Imports can be increased by the following:

- More reliable dynamic rating of line limits
- Optimal generator voltages
- Optimal settings of grid equipment (CBs, OLTCs, PARs, DC lines, SVCs)
- Demand-side management (identifying load pockets with problems)
- Optimal selection of new equipment (type, size, location)

Natural reduction of losses, reduction of VAR consumption, reduction of equipment stress

Dependence of feasible interconnection transfer on scheduling practices—real opportunities for IT

- Base case for the given NPCC system in 2002 and the 2007 projected load
- Case #1-the same, except the entire real power generation was re-scheduled in order to support an increased wheel from PJM (Alburtis) through NYISO to IESO (Milton) –the maximum feasible wheel 1,200MW
- Case #2-the wheel from PJM (Waldwick) through NYISO to IESO (Milton) –the maximum wheel feasible 100MW

Effects of Voltage Scheduling in Support of Higher Power Transfers

- With the voltage scheduling optimized within +/- .03pu range, w/o any real power rescheduling the maximum power transfer increased to 2,900MW into both Alburtis and Waldwick;
- With the voltage scheduling optimized within +/- .05pu the feasible transfer increased to 3,100MW at both Alburtis and Waldwick.
- With both voltages optimized within +/-.05pu and real power re-scheduled by the NYISO, the maximum wheel possible around 8,800MW

Effects of Phase Angle Regulators (PARs)

Scheduling of the Tie-Lines between the Control Areas

- Case #1—with PARs scheduling within their maximum capacity limits, wheel of 8,800MW possible by using real power generation only.
- Case #2—with PARs , the maximum wheel into Waldwick without re-scheduling real power inside NYISO is 500MW (a 400MW increase)
- PARs HAVE HUGE EFFECTS ON FEASIBLE TRANSFERS ACROSS CONTROL AREAS.
- MAKING THESE MOST OPTIMAL AT THE INTERCONNECTION LEVEL REQUIRES ON-LINE COORDINATION ACROSS THE CONTROL AREAS.
- Thermal limits for PARs are weather dependent and therefore require reliable DLR units to rely on with confidence

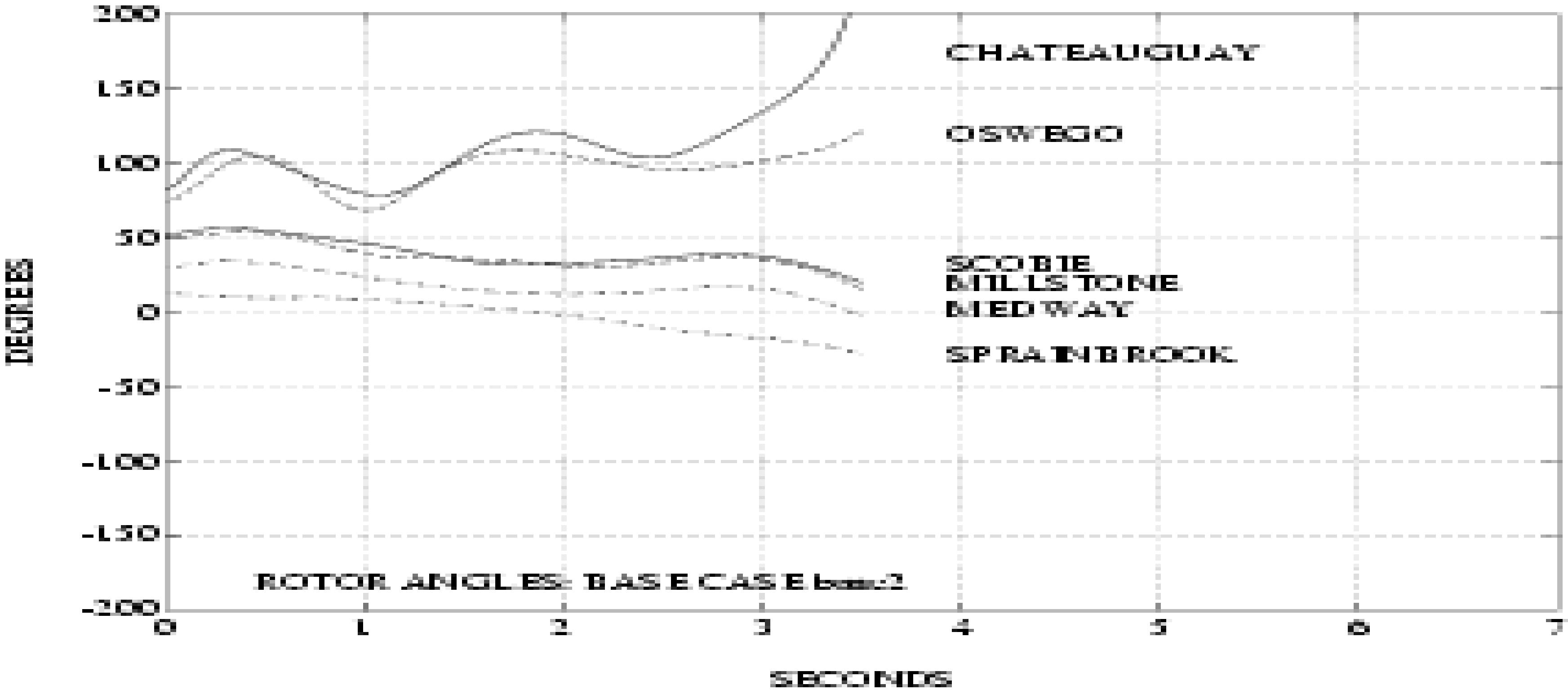
Major transient stability problems [5,6]

- A 38-bus, 29 machine equivalent dynamic model of the NPCC system
- It was shown to reproduce a multi-machine oscillation that occurred at .75Hz, involving groups of machines in NYC (modeled as Sprainbrook generator) and the northeastern part of New York State, as well as parts of Canadian power system (modelled primarily by the Oswego and Chateaguay units);
- The fault scenario selected for this test was a five-cycle three-phase short circuit of the Selkrik/Oswego transmission line carrying 1083MW. The oscillation grows until the Chateaguay generator loses synchronism, followed shortly by the Oswego unit.

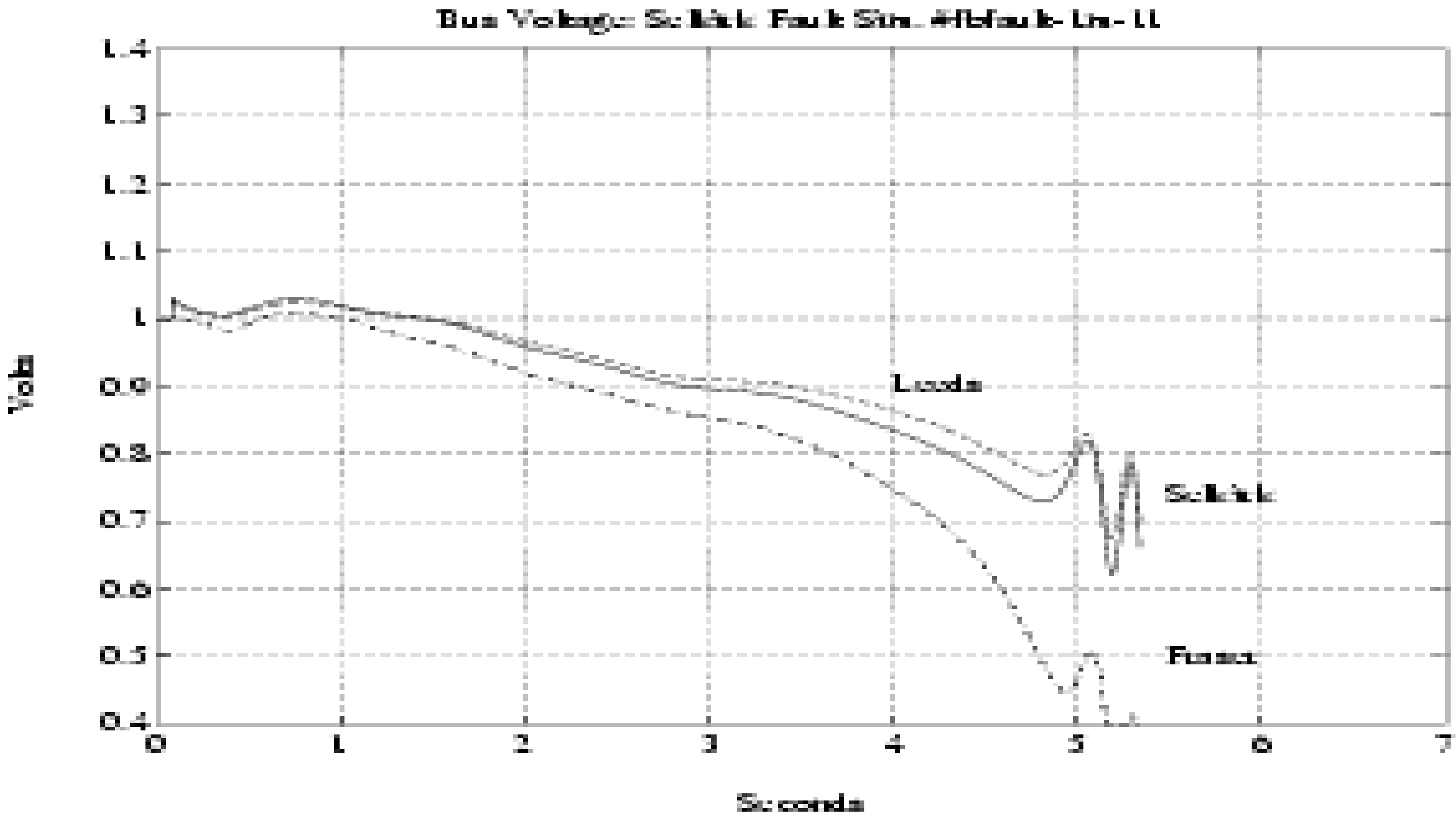
Issues with ensuring AC synchronism

- Many root causes of instabilities in today's industry (large equipment failures, large deviations in system load away from the conditions for which the primary controllers are tuned) [5,6]
- Newly evolving transient stability problems in response to sudden prolonged wind gusts [7,8]
- Small-signal robustness problems [9,10]

Rotor angles -- base case for Selkrik fault

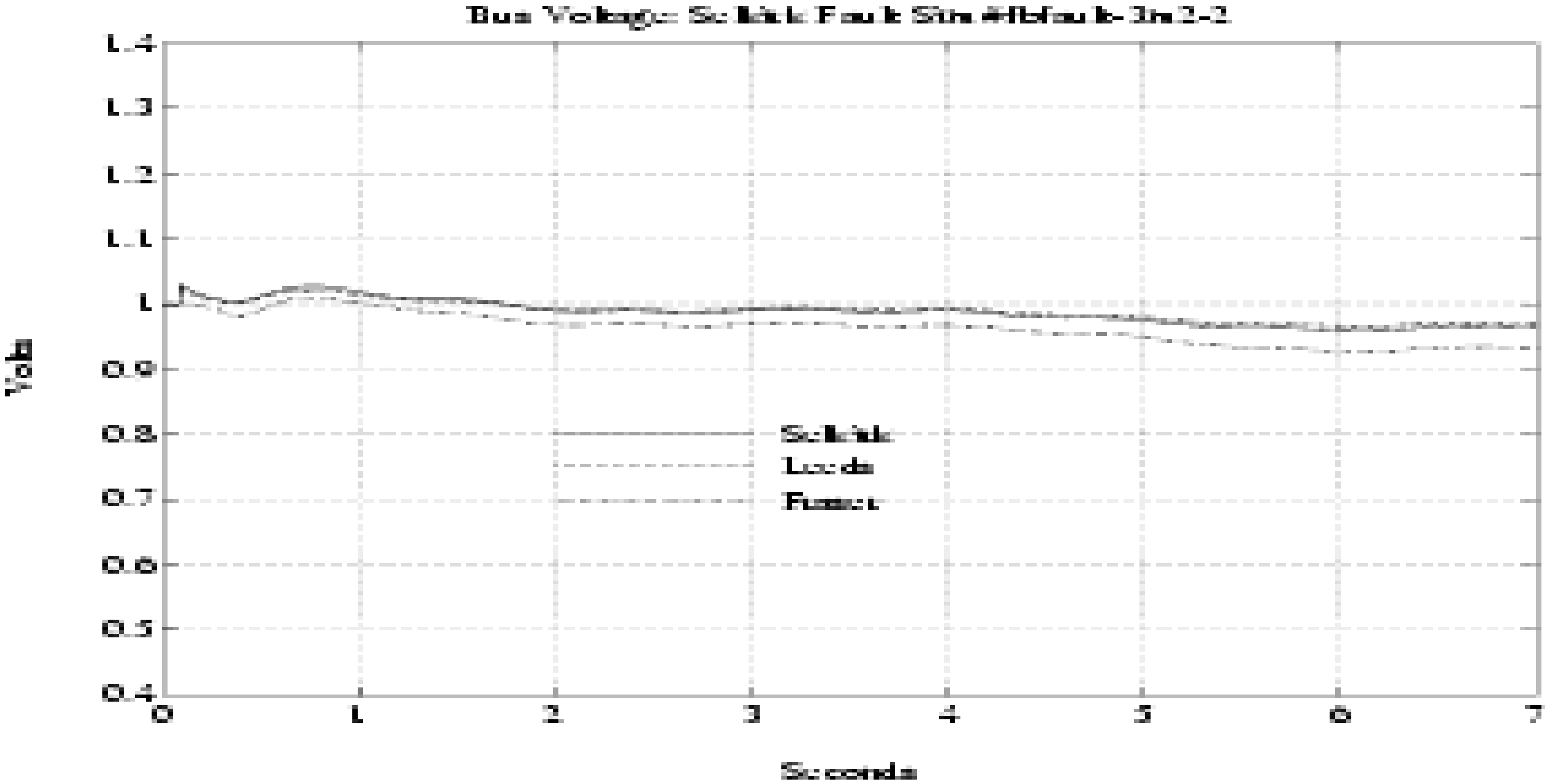


Voltage response with conventional controllers-base case Selkrik fault



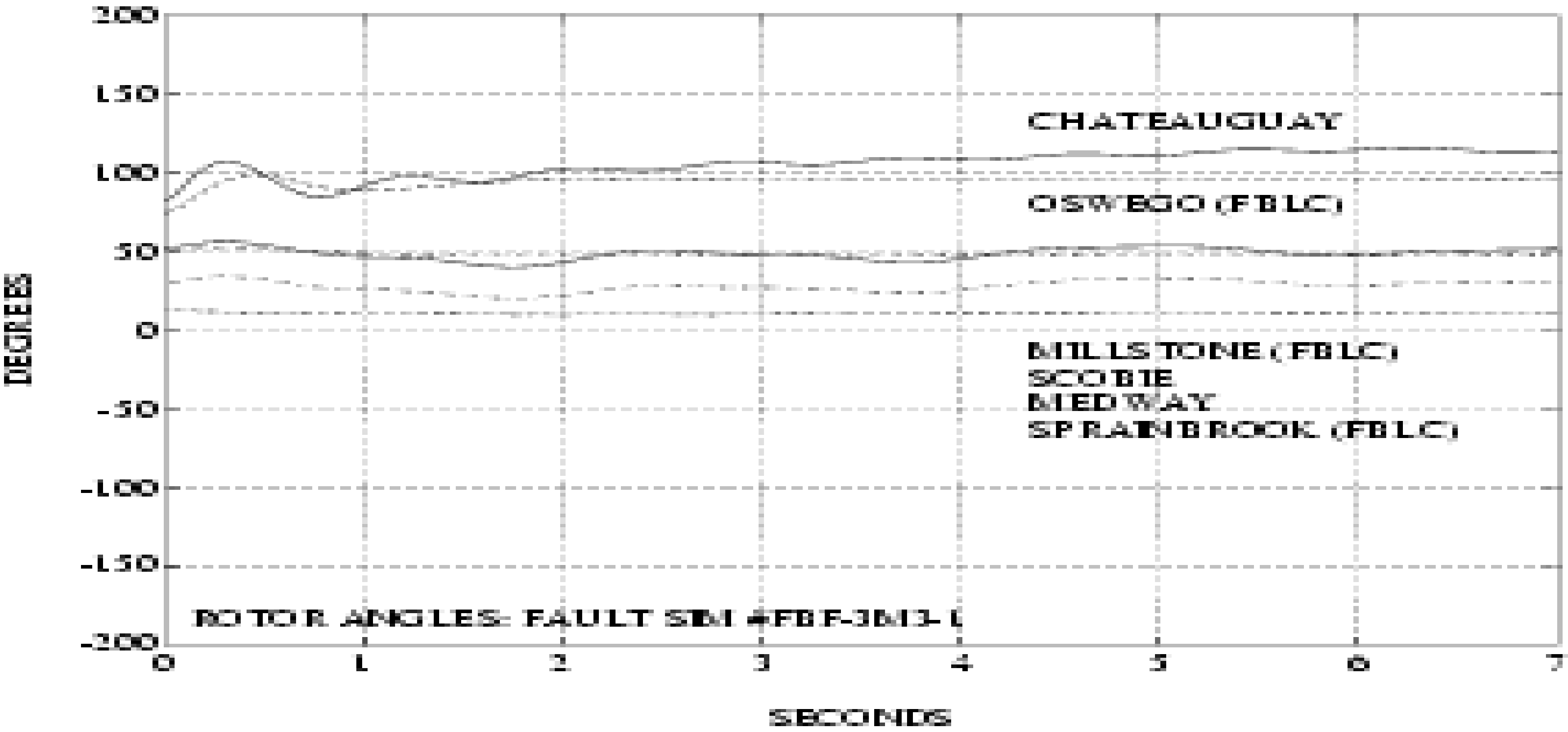
This talk is partially based on the IEEE Proc. paper Nov 2005

Bus voltages with new controllers [5,6]



This talk is partially based on the IEEE Proc. paper, Nov 2005

Rotor angle response with distributed controllers (FBLC+ODSS) [5,6]-an early example of flat control design

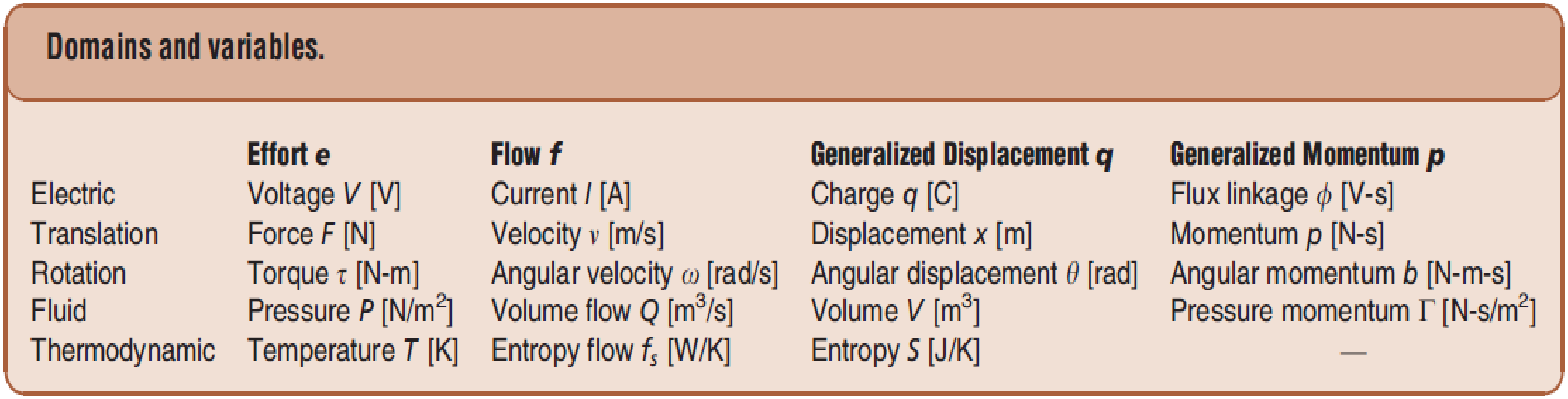


This talk is partially based on the IEEE Proc. paper Nov 2005

Major challenge and opportunity for distributed control and estimation

- Can we have plug-and-play distributed control to support distributed scheduling (feed-forward)?
- Sensing, communications to ensure dynamic observability and controllability
- The key question: How distributed can dynamic controllers and observers become?

Modeling Dynamics of Electric Energy Systems



Domains and variables.

	Effort e	**Flow f**	**Generalized Displacement q**	**Generalized Momentum p**
Electric	Voltage V [V]	Current I [A]	Charge q [C]	Flux linkage ϕ [V-s]
Translation	Force F [N]	Velocity v [m/s]	Displacement x [m]	Momentum p [N-s]
Rotation	Torque τ [N-m]	Angular velocity ω [rad/s]	Angular displacement θ [rad]	Angular momentum b [N-m-s]
Fluid	Pressure P [N/m^2]	Volume flow Q [m^3/s]	Volume V [m^3]	Pressure momentum Γ [N-s/m^2]
Thermodynamic	Temperature T [K]	Entropy flow f_s [W/K]	Entropy S [J/K]	—

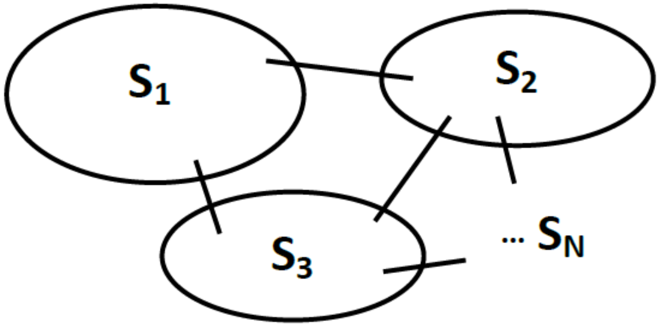
$$\underline{x} = \Big[\underbrace{I_L, V_C,}_{\text{Electrical States}} \quad \underbrace{v_{mass}, F_{spring},}_{\text{Mechanical States}} \quad \underbrace{f_S, T}_{\text{Thermodynamic States}}\Big]$$

$$\frac{d\underline{x}}{dt} = \underline{f}\left(\underline{x}, \underline{u}, \underline{p}\right), \qquad \underline{x}(0) = \underline{x}_0$$

Table from: D. Jeltsema and J.M.A. Scherpen. Multidomain modeling of nonlinear networks and systems. Control Systems Magazine, Aug. 2009

Structure of Interconnected Power Systems [8,10]

At the System Level



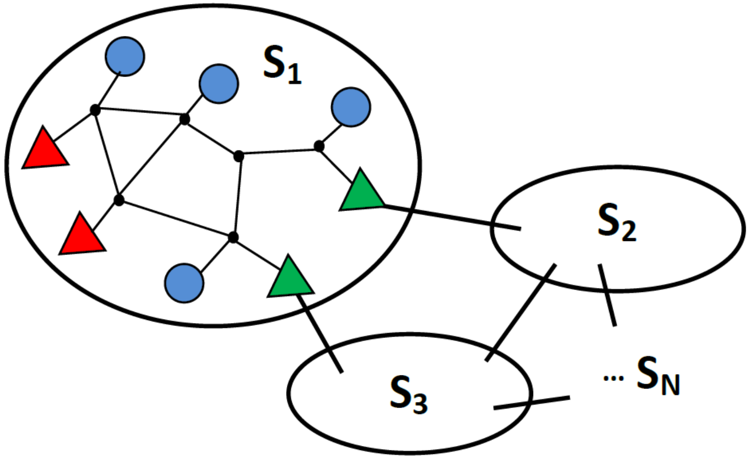
S_K The K-th subsystem
K=1,2,…N

Interconnected by transmission lines

Modeling covers

- **Components**
- **Network coupling constraints**
- **Subsystems**
- **Entire system**

At the Subsystem Level



● Dynamical component

🔺 Internal disturbance source

▲ External disturbance source

Interconnected by transmission lines

Important model structure

- Subsystem

$$\dot{\underline{\boldsymbol{x}}}^K = \boldsymbol{A}^K \underline{\boldsymbol{x}}^K + \boldsymbol{B}^K \underline{\boldsymbol{u}}_{gl}^K + \boldsymbol{F}_{in}^K \underline{\boldsymbol{d}}_{in}^K + \boldsymbol{F}_{ex}^K \underline{\boldsymbol{d}}_{ex}^K \tag{4}$$

- Entire system

$$\underline{\boldsymbol{x}} = \begin{bmatrix} \underline{\boldsymbol{x}}^1 \\ \underline{\boldsymbol{x}}^2 \\ \vdots \\ \underline{\boldsymbol{x}}^N \end{bmatrix}, \quad \underline{\boldsymbol{u}}_{gl} = \begin{bmatrix} \underline{\boldsymbol{u}}_{gl}^1 \\ \underline{\boldsymbol{u}}_{gl}^2 \\ \vdots \\ \underline{\boldsymbol{u}}_{gl}^N \end{bmatrix}, \quad \underline{\boldsymbol{d}}_{in} = \begin{bmatrix} \underline{\boldsymbol{d}}_{in}^1 \\ \underline{\boldsymbol{d}}_{in}^2 \\ \vdots \\ \underline{\boldsymbol{d}}_{in}^N \end{bmatrix},$$

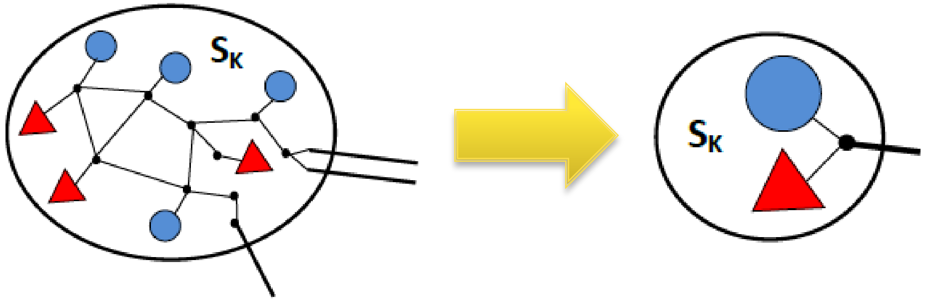
N **Total number of subsystems**

$$\dot{\underline{\boldsymbol{x}}} = \boldsymbol{A}\underline{\boldsymbol{x}} + \boldsymbol{B}\underline{\boldsymbol{u}}_{gl} + \boldsymbol{F}_{in}\underline{\boldsymbol{d}}_{in} \tag{5}$$

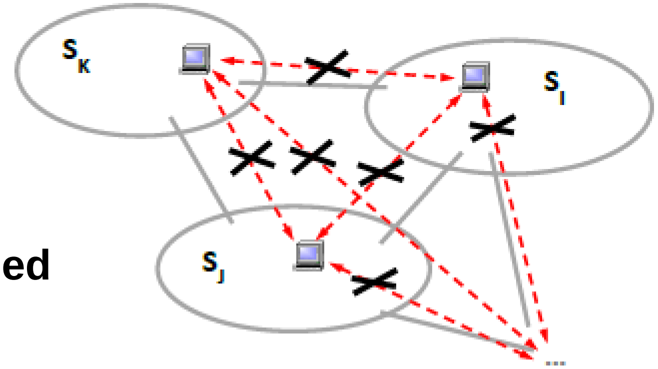
Conventional AGC Standard

- Fundamental assumptions

Lumped model



Decentralized Control

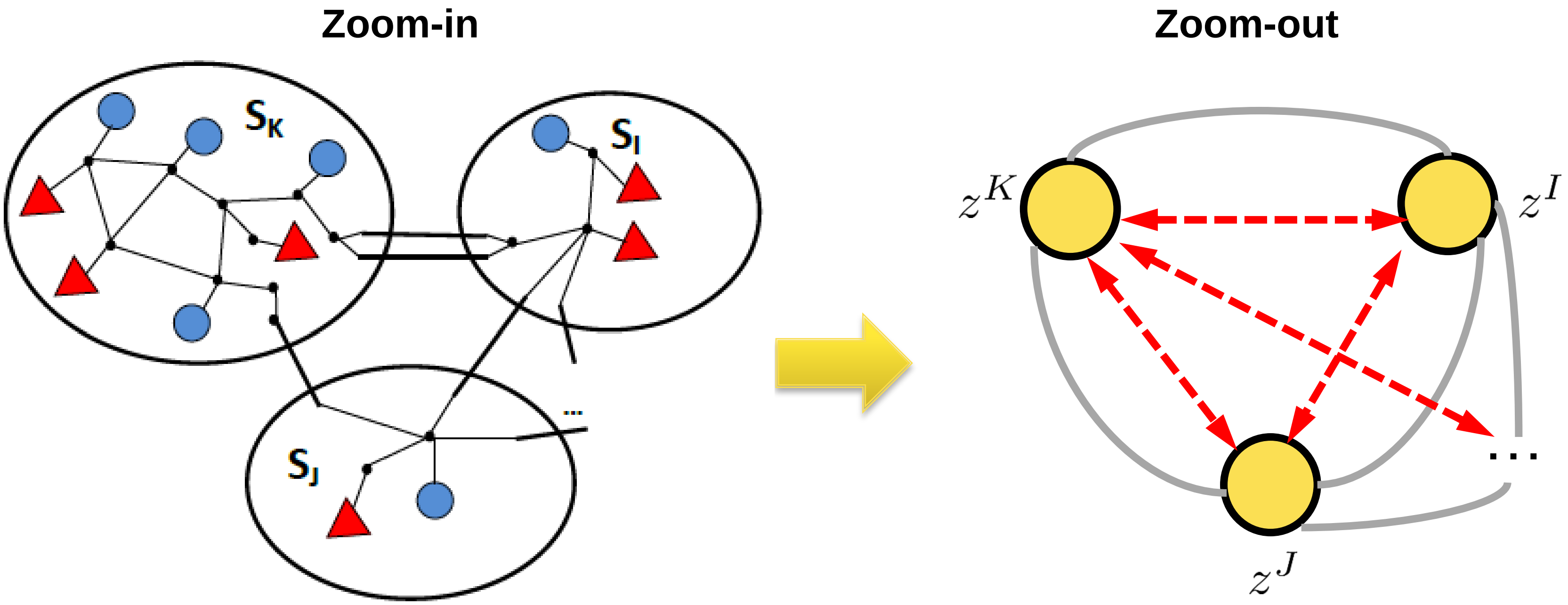


Problems

- Lumped Model: losing structures, only valid in steady state
- Decentralized Control: uneconomical at the system level

Our proposed structure-based approach [8,10]

- Minimal coordination by using an aggregation-based notion of dynamic "interactions variable"



Existence of interaction variable

- ❖ Model-based derivation for interactions variable (IntV)

$$\underline{\dot{\boldsymbol{x}}}_s^K = \boldsymbol{A}_{ss}^K \underline{\boldsymbol{x}}_s^K + \boldsymbol{A}_{sp}^K \underline{\boldsymbol{P}}_T^K + \boldsymbol{F}_{s,in}^K \underline{\mathbf{d}}_{in}^K + \boldsymbol{F}_{s,ex}^K \underline{\mathbf{d}}_{ex}^K$$

Structure of any Subsystem model

Important property: A_{ss}^K **structurally singular with (N-1) rank deficiency due to linear dependence of power network constraints.**

$$\exists\, \boldsymbol{T}_a^K, \quad s.t. \;\; \boldsymbol{T}_a^K \boldsymbol{A}_{ss}^K = 0$$

Dynamics of interactions variable (IntV) and its physical interpretation

- IntV is defined as a linear combination of internal states

$$z_a^K = \boldsymbol{T}_a^K \underline{\boldsymbol{x}}_s^K$$

$$\dot{z}_a^K = \boldsymbol{T}_a^K \boldsymbol{A}_{sp}^K \underline{\boldsymbol{P}}_T^K + \boldsymbol{T}_a^K \boldsymbol{F}_{in}^K \underline{\boldsymbol{d}}_{in}^K + \boldsymbol{T}_a^K \boldsymbol{F}_{ex}^K \underline{\boldsymbol{d}}_{ex}^K$$

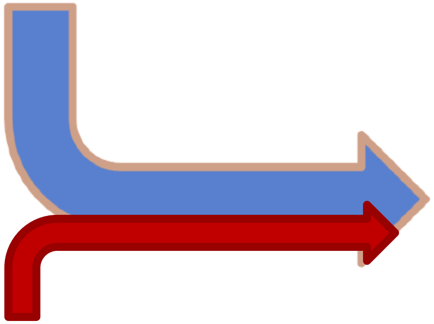
Only driven by local control and internal and external disturbances.
Represents the interaction of the subsystem to the entire system

$$z_a^K(t) = \boldsymbol{T}_a^K \underbrace{\boldsymbol{A}_{sp}^K \int_{t_0}^{t} \underline{\boldsymbol{P}}_T^K d\tau}_{\substack{\textbf{Mechanical energy}\\ \sum E_{Mech}^K}} + \underbrace{\boldsymbol{T}_a^K \boldsymbol{F}_{in}^K \int_{t_0}^{t} \underline{\boldsymbol{d}}_{in}^K d\tau + \boldsymbol{T}_a^K \boldsymbol{F}_{ex}^K \int_{t_0}^{t} \underline{\boldsymbol{d}}_{ex}^K d\tau}_{\substack{\textbf{Electrical energy taken by the disturbances}\\ \sum E_{Elec}^K}}.$$

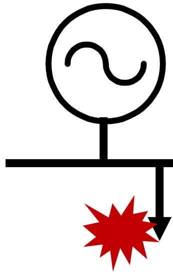
Physical interpretation of IntV

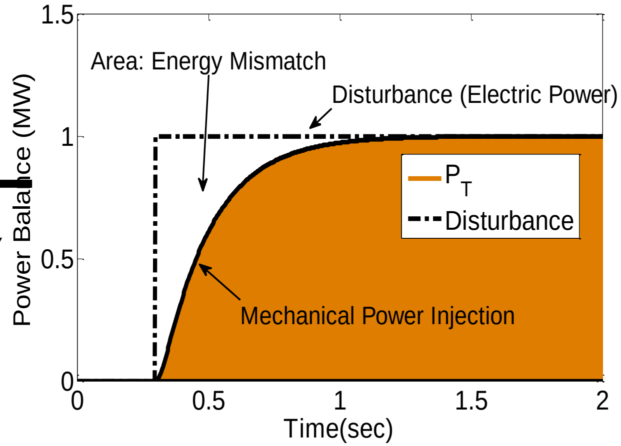
Energy mismatch $z_a^K = \sum E_{Mech}^K + \sum E_{Elec}^K = \Delta E_{Stored}$

Mechanical Energy injection



Electrical energy consumption





Stored energy Excursion on stored energy causes deviations on frequency

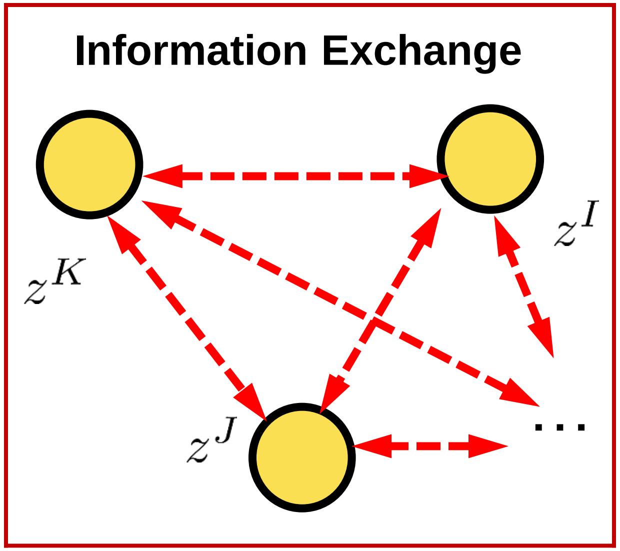
Hypothesis

- IntV contains key information to represent the subsystem's response
- Bringing IntV to zero the consequently returns system frequency to the original equilibrium

IntV-based minimal coordination

- Feedback control design for E-AGC

$$
\begin{aligned}
\underset{\boldsymbol{u}_{gl}}{\text{minimize}} \quad & J = \frac{1}{2}\int_0^\infty \left({\underline{\boldsymbol{z}}_a}^T \boldsymbol{Q} \underline{\boldsymbol{z}}_a\right) dt + \int_0^\infty \left({\underline{\boldsymbol{u}}_{gl}}^T \boldsymbol{R} \underline{\boldsymbol{u}}_{gl}\right) dt \\
\text{subject to} \quad & \underline{\dot{\boldsymbol{x}}} = \boldsymbol{A}\underline{\boldsymbol{x}} + \boldsymbol{B}\underline{\boldsymbol{u}}_{gl} \\
& \underline{\boldsymbol{z}}_a = \boldsymbol{T}_a \underline{\boldsymbol{x}} \\
& \underline{\boldsymbol{u}}_{gl} = -\boldsymbol{L}\underline{\boldsymbol{z}}_a,
\end{aligned}
$$



Remark

- T_a^K is a non-invertible vector, so exchange of IntV will not reveal the confidential information

Possible ways of adapting primary controllers

- More adaptive decentralized controllers (various nonlinear high-gain controllers—sliding mode control; feedback-linearizing control (FBLC); observation decoupled state space combined with FBLC logic)
- A combination of coordinating signals and change of logic (coordinating signals identifying when the system response is qualitatively different and it requires change in control logic in order to stabilize dynamics)
- NONE OF THE CURRENTLY IMPLEMENTED CONTROLLERS ARE ADAPTIVE except the multi-modal Hydro-Quebec PSS)

Possible role of enhanced control during abnormal conditions [5,6]

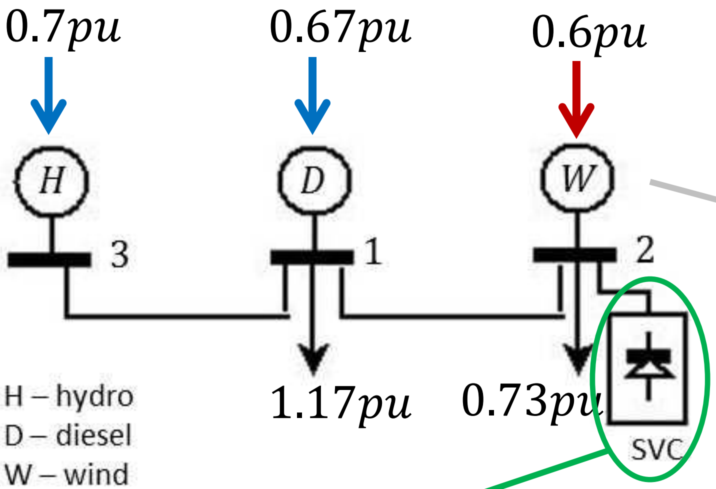
- Adjust logic of primary controllers to avoid instability problems;
- Systematic coordination of the remaining resources to prevent steady-state imbalances and additional congestion (adjust settings on voltage support equipment, adjust power generated to avoid imbalances) [12,21]

Summary of potential of high-gain controllers

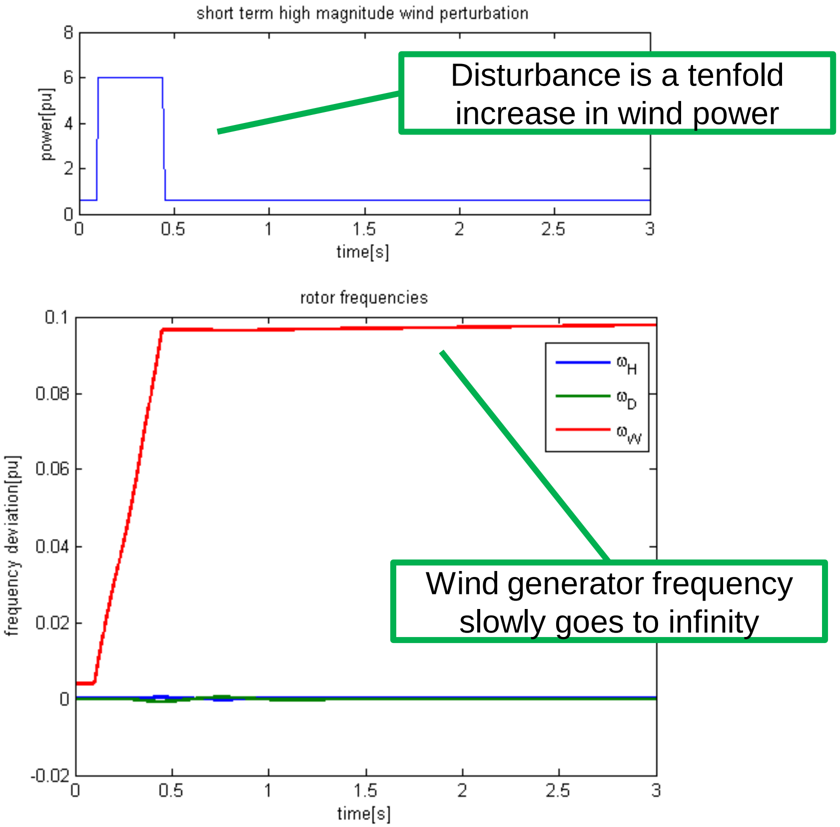
- It is possible that these controllers could avoid loss of synchronism while the conventional controllers can not
- The same controllers are ideal for preventing sub-synchronous resonance [3].
- Therefore critical to consider while designing SPS of the future
- No fast communications required. Therefore simple to implement.
- Major observation: Nonlinear high-gain feedback cancels interactions with the rest of the system and makes the system LTI on closed loop.

Issues with Large Wind Disturbances [7,8]-unstable interactions with the rest of the system

- Types of large disturbances causing transient instabilities
  - High wind surges in Flores Island
  - Failures of equipment and faults
- Frequency instability



Controller: Static Var Compensator (SVC)

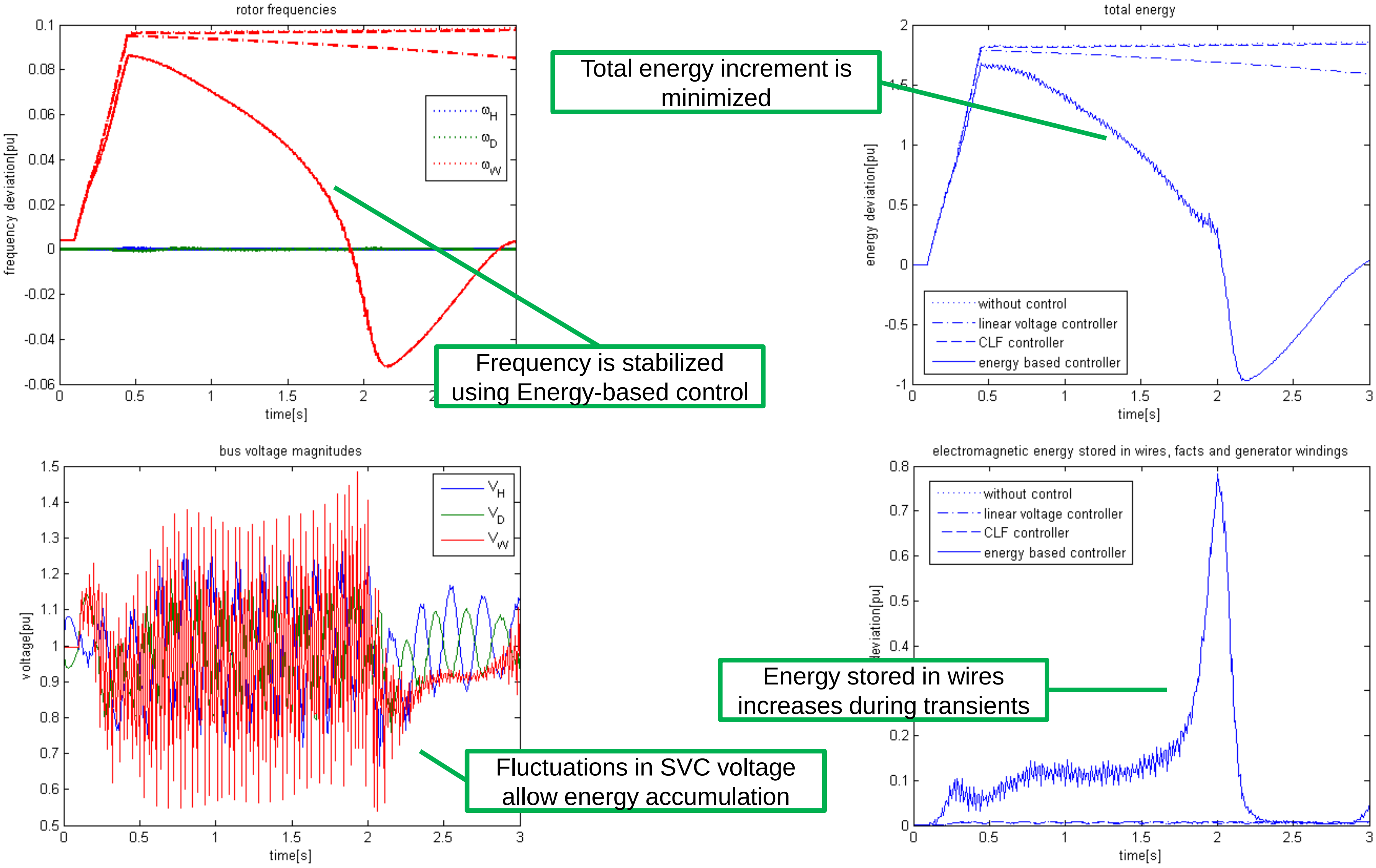


Disturbance is a tenfold increase in wind power

Wind generator frequency slowly goes to infinity

Key role of FACTS control for managing transfer of stored energy

🟦 Hydro
🟩 Diesel
🟥 Wind
▪▪▪▪▪ Uncontrolled system
▬ ▪ ▬ Other control strategies



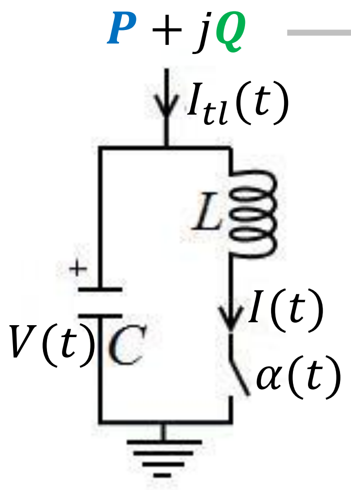
Total energy increment is minimized

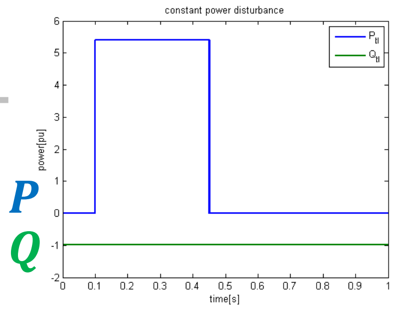
Frequency is stabilized using Energy-based control

Energy stored in wires increases during transients

Fluctuations in SVC voltage allow energy accumulation

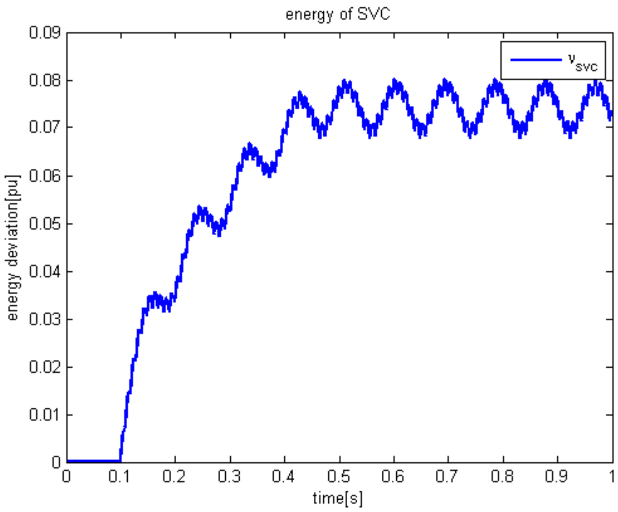
Using FACTS Devices as Temporary Energy Storage

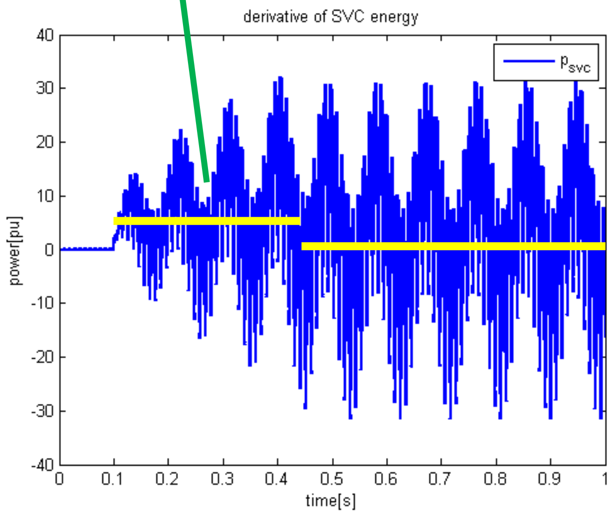




- Exploit the fact that reactive elements can accumulate active power during transients

Active power is different than zero on the average and it is equal to the size of the constant power disturbance ***P***



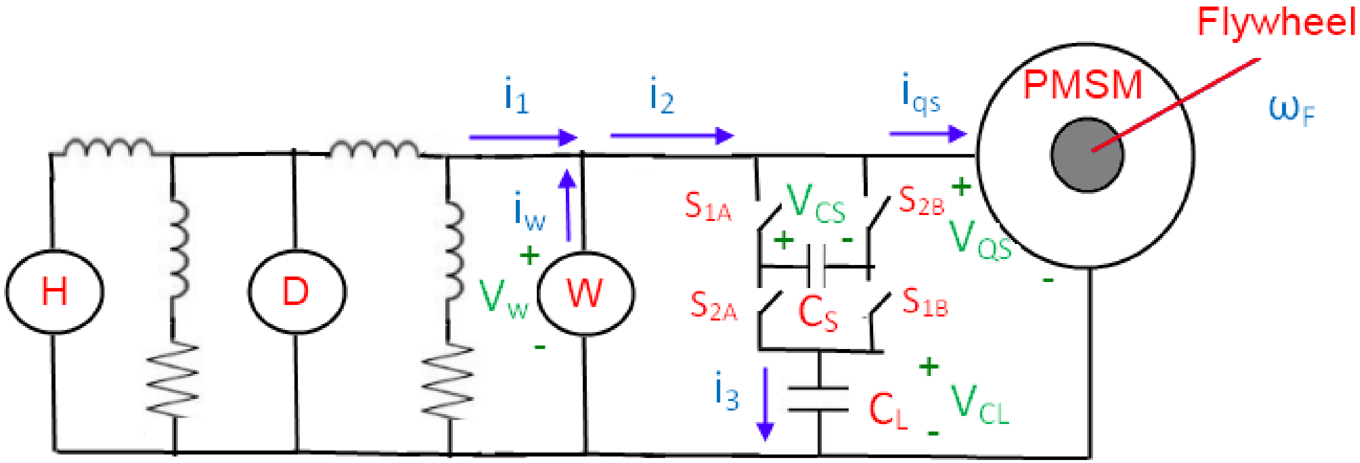


$$v(t) = \frac{1}{2}L\tilde{I}^2(t) + \frac{1}{2}C\tilde{V}^2(t)$$

$$p(t) = \frac{dv(t)}{dt} = L\tilde{I}(t)\frac{d\tilde{I}(t)}{dt} + C\tilde{V}(t)\frac{d\tilde{V}(t)}{dt}$$

$$\boldsymbol{P} = \frac{1}{T}\int_0^T p(t)dt$$

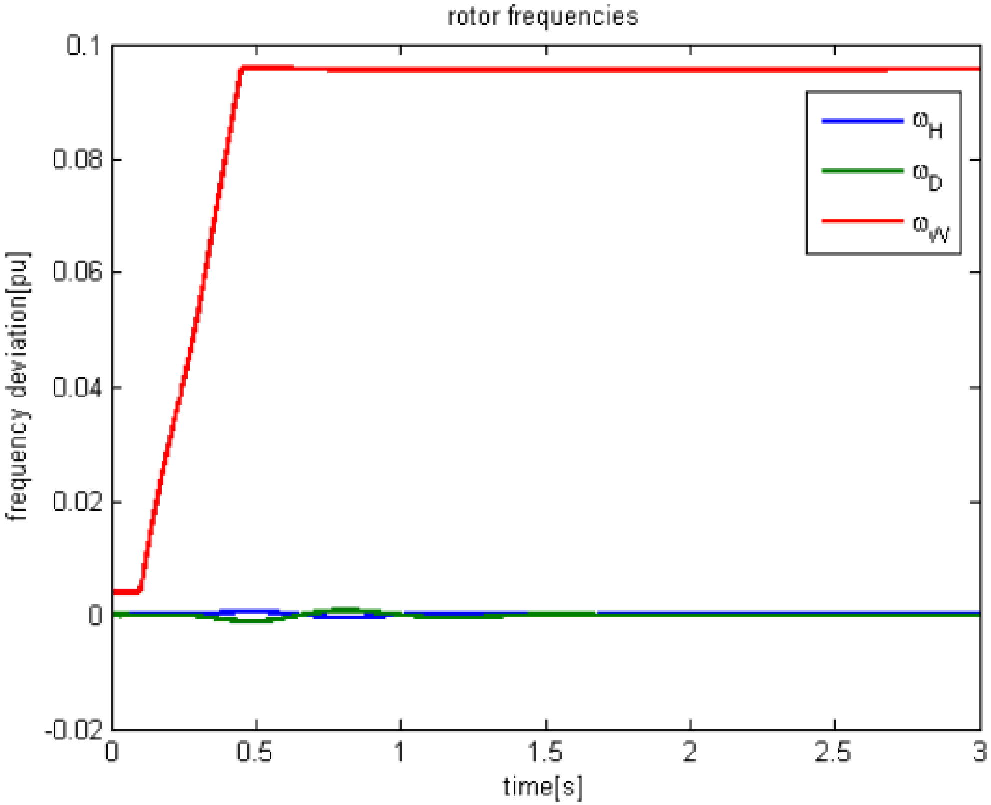
Potential of sliding mode control using flywheels (Flores) –the same as FACTS



- Switches open and close at very high frequency relative to rest of the grid
- Large capacitor (C_L) serves to keep the voltage across the wind generator nearly constant
- The polarity of the small capacitor (C_s) changes to control i_{qs}

Use Flywheel for Frequency Stabilization

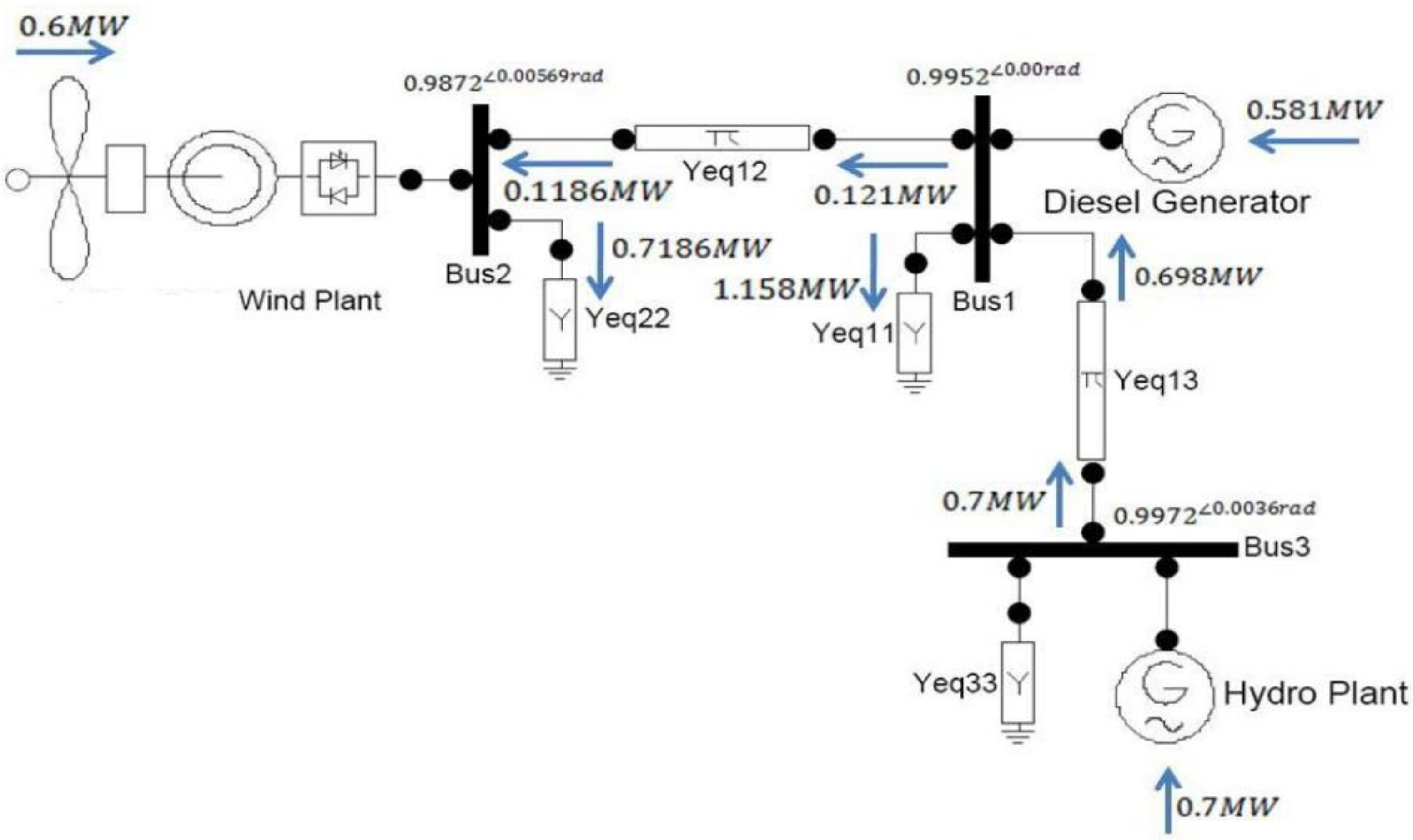
- Include dynamics of the entire system
- Set i_{qs}^{*}=0A in order to stabilize the disturbance



Issues with small signal stability [9-11]

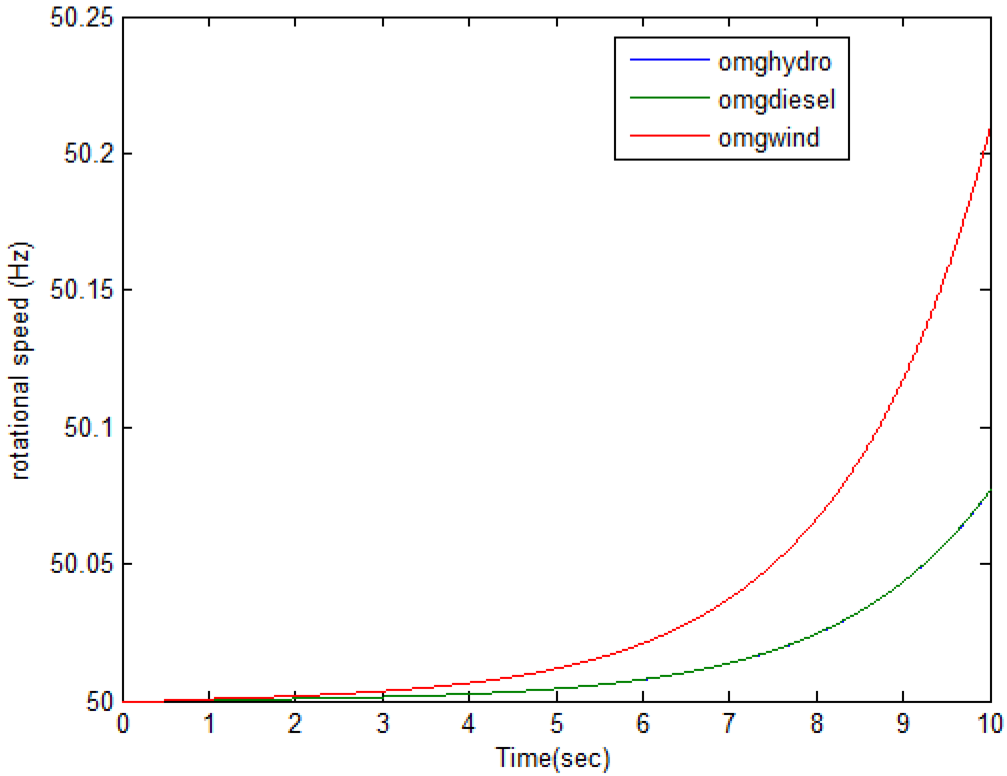
- Today’s approach is to tune individual primary controllers (governors, DFIG of wind power plants, excitation systems) so that they are stand-alone stable for the assumed ``worst-case” system condition.
- All controllers are constant gain decentralized PID controllers responding to the local output variables (voltage magnitude, frequency).
- No reliance on communications.
- Small signal stability analysis run for the closed-loop system dynamics to ensure that linearized system dynamics are stable.
- Missed opportunity to design PMU-based primary control for ensuring small signal stabilization (with minimal communications).

Flores island system



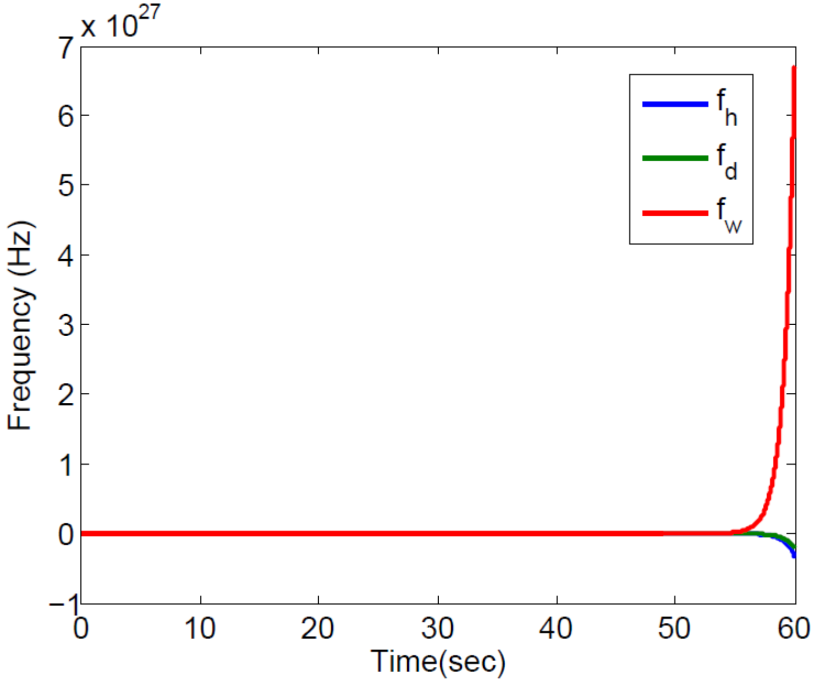
Critical role of primary control

- Unstable Flores System without Governor and Excitation Control

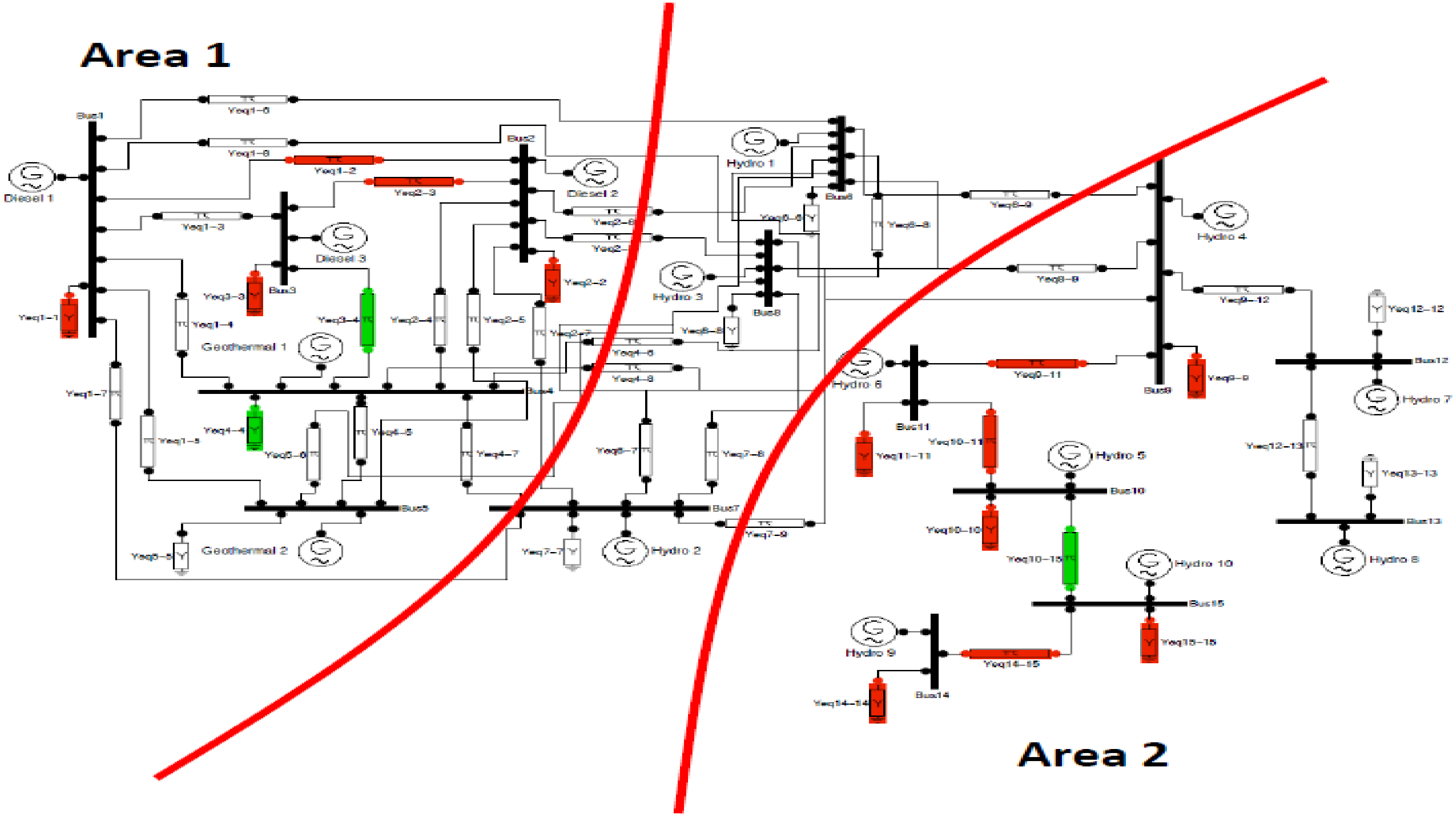


Critical role of excitation control

- Weak connection, unstable system due to insufficient reactive power support



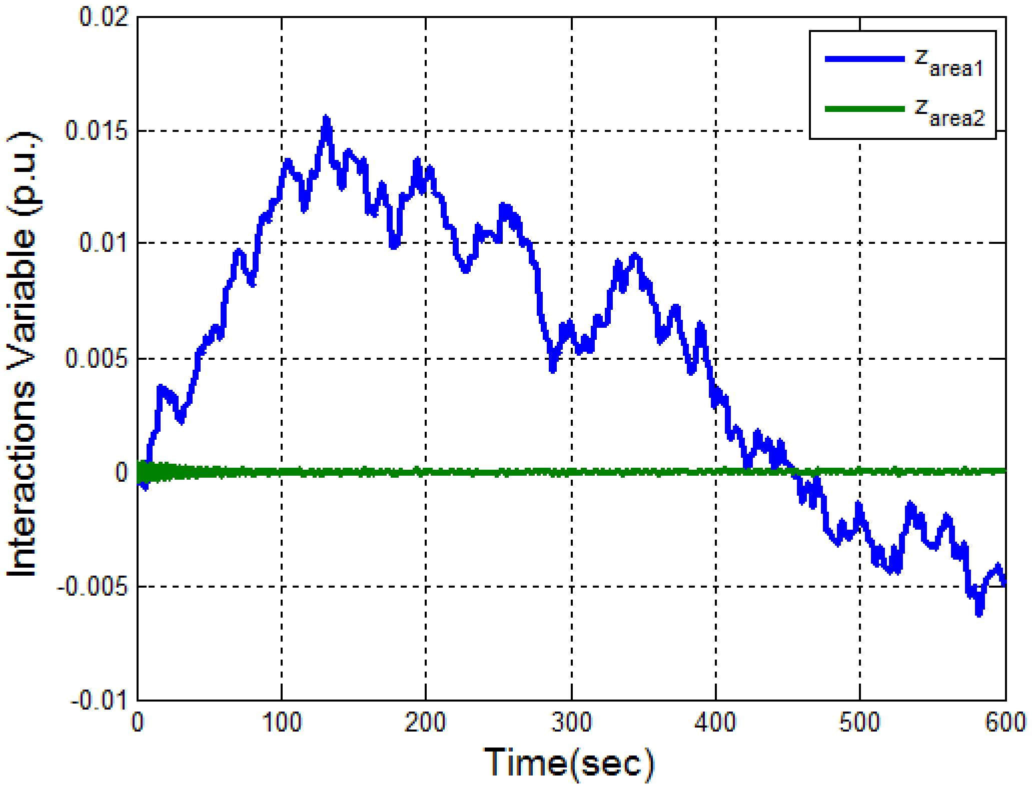
Dynamics of interaction variables between the areas—Sao Miguel System



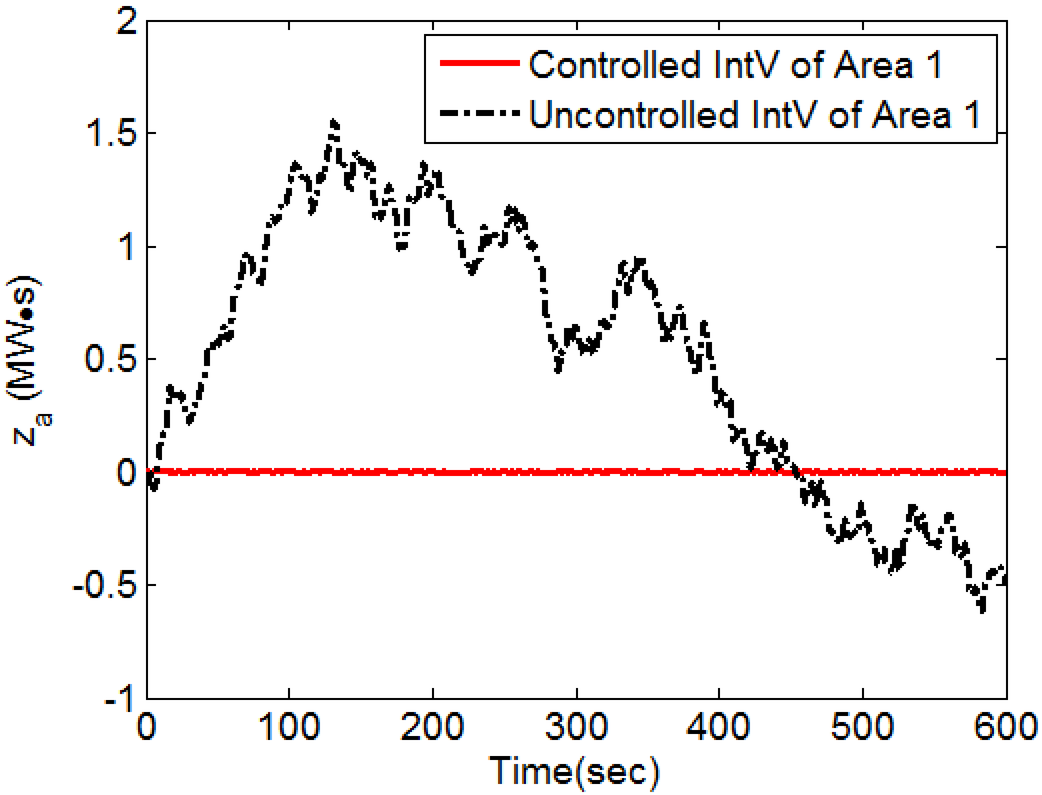
[2] M. Ilic “The Tale of Two Green Islands in the Azores Archipelago,” Chapter 2 of Engineering IT-Enabled Sustainable Electricity Services : The Tale of Two Low-Cost Green Azores Islands.

Key notion of interaction variable dynamics and their control

- Interactions variables of area-1 and area-2

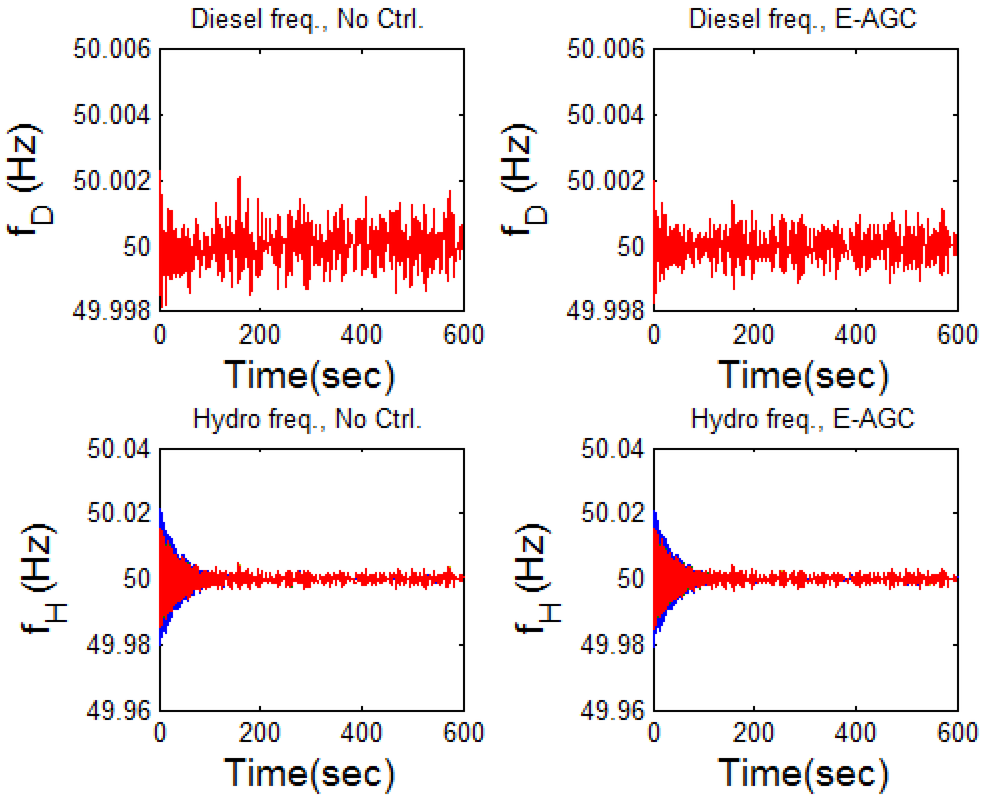


- Controlled IntV v.s. uncontrolled IntV



Issues with intra-area dynamics

- Other states [still oscillations]



Given technology, comparison of regular and advanced AGC (LQR) –a sample

Case 1: Zero Mean Wind Disturbances (Good Wind Prediction)

Wind in this case is operating at its full capacity (Pw = 0.6 MW) and the prediction can be accurate.

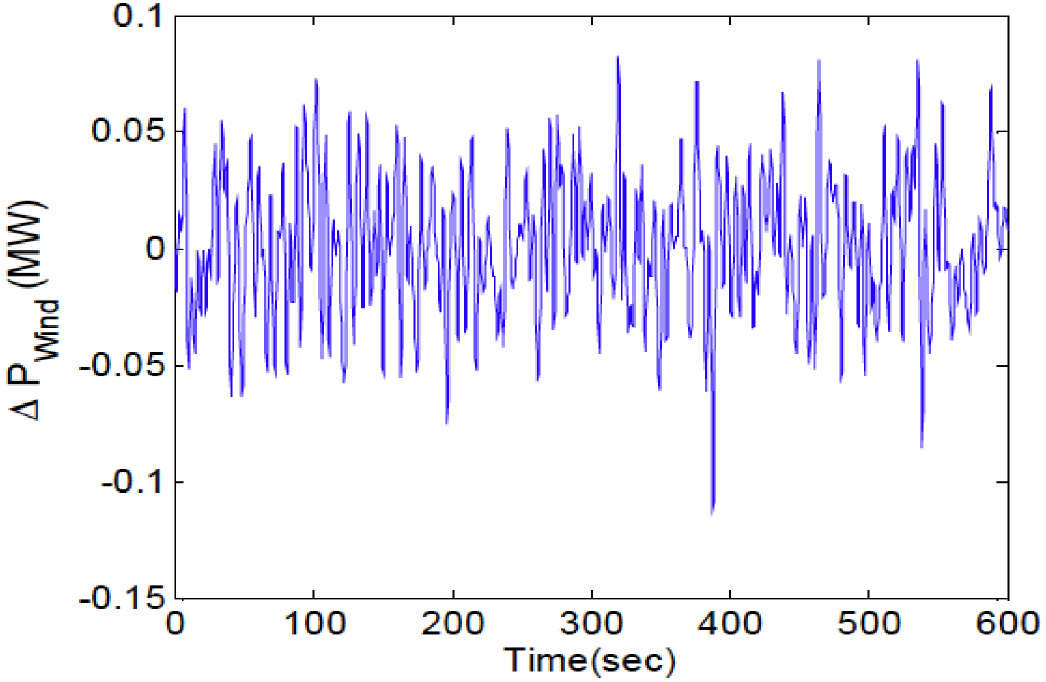
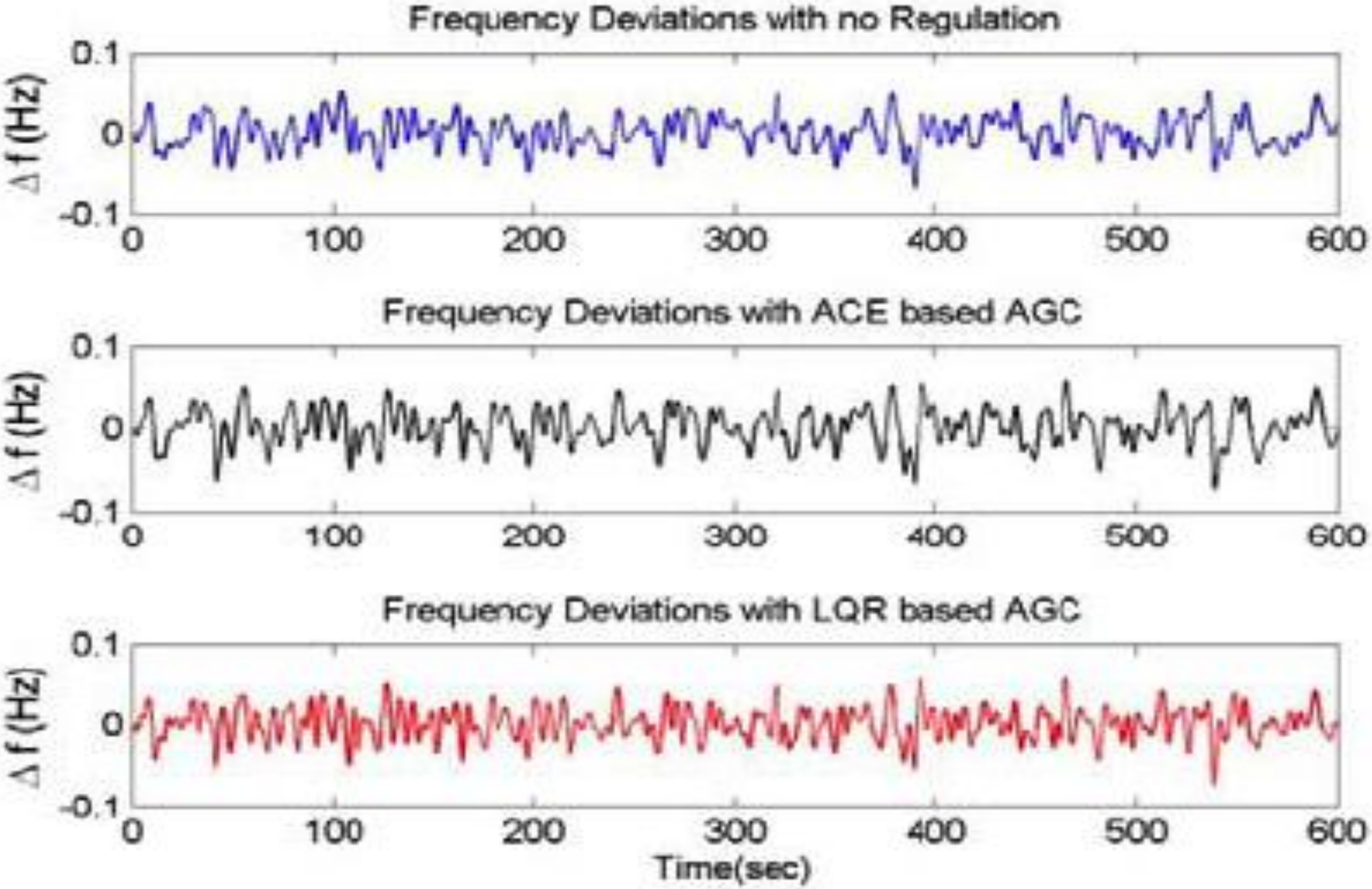
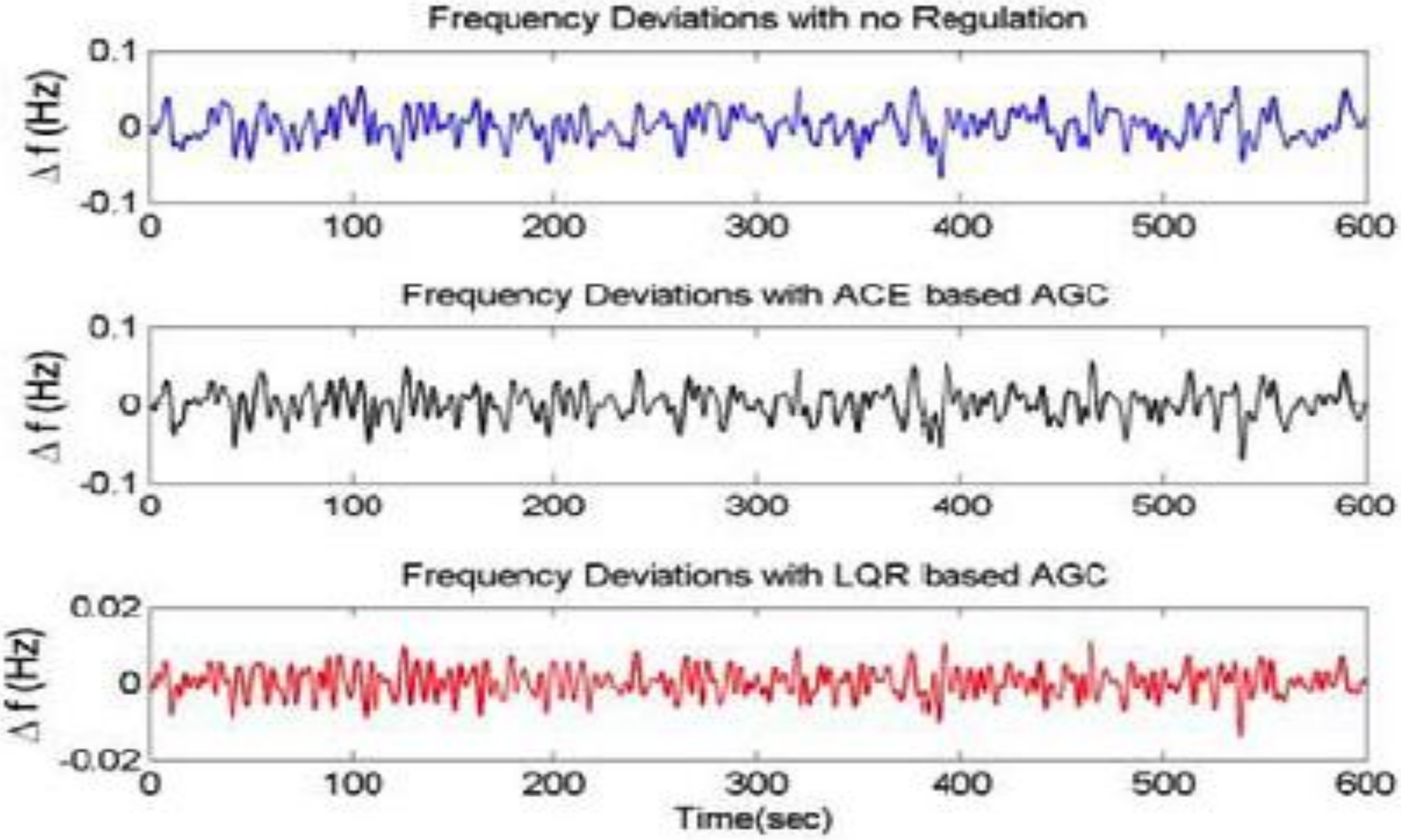


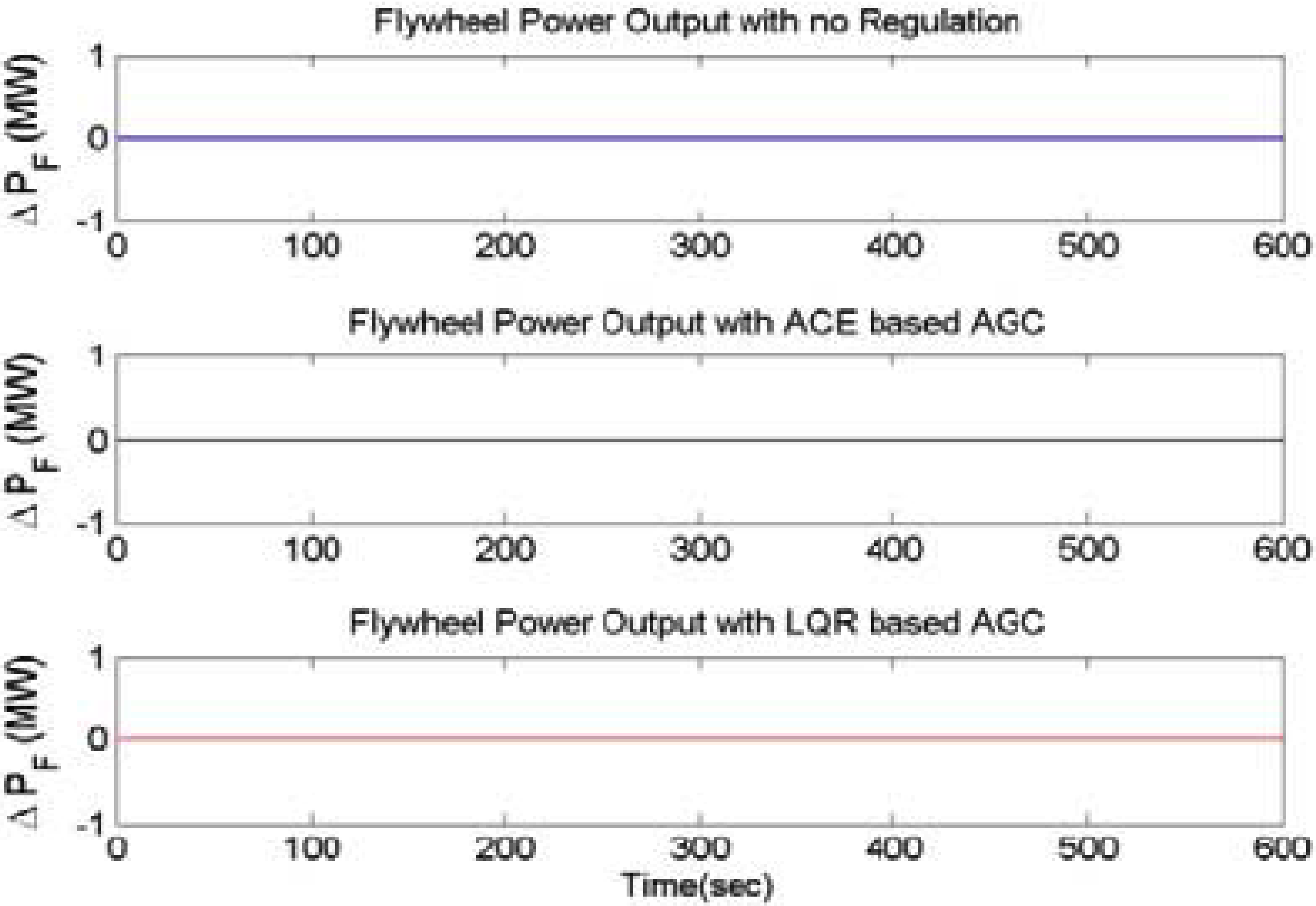
Figure 1.1 Zero Mean Wind Disturbances and 5% Standard Deviation around the Operating Point in 10 minutes.



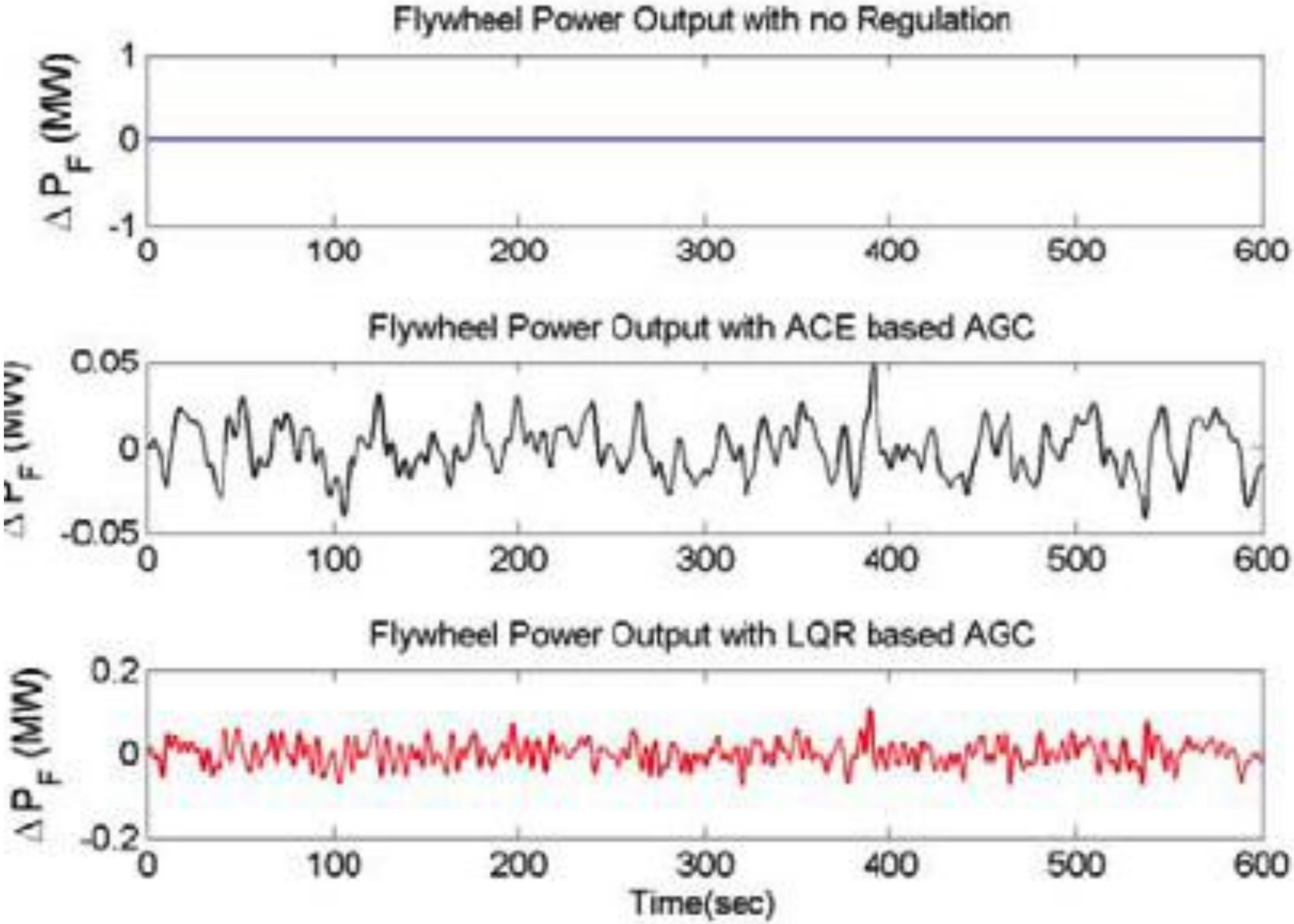
(a) AGC with Hydro Only



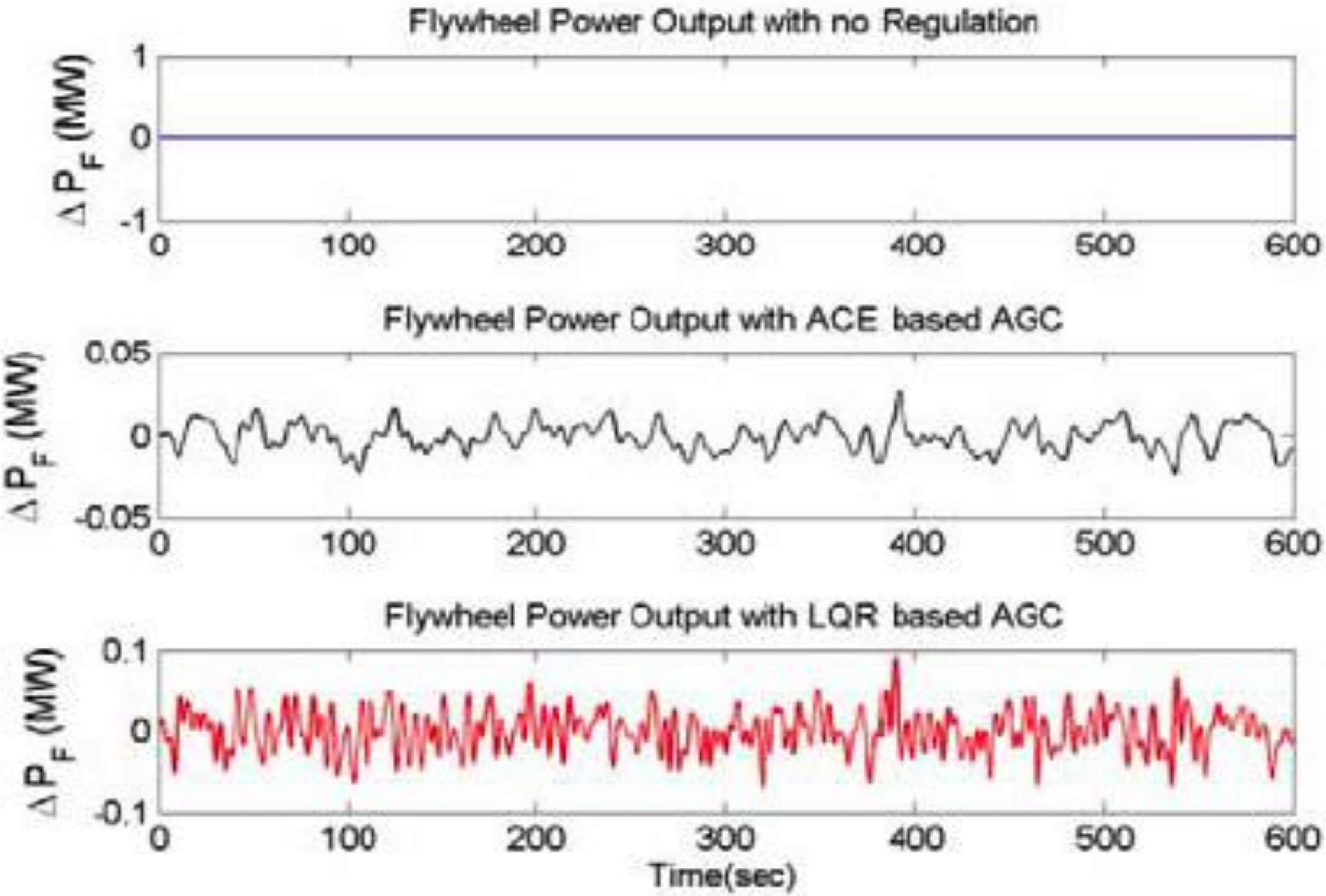
(d) AGC with Diesel and Flywheel



(a) AGC with Hydro Only

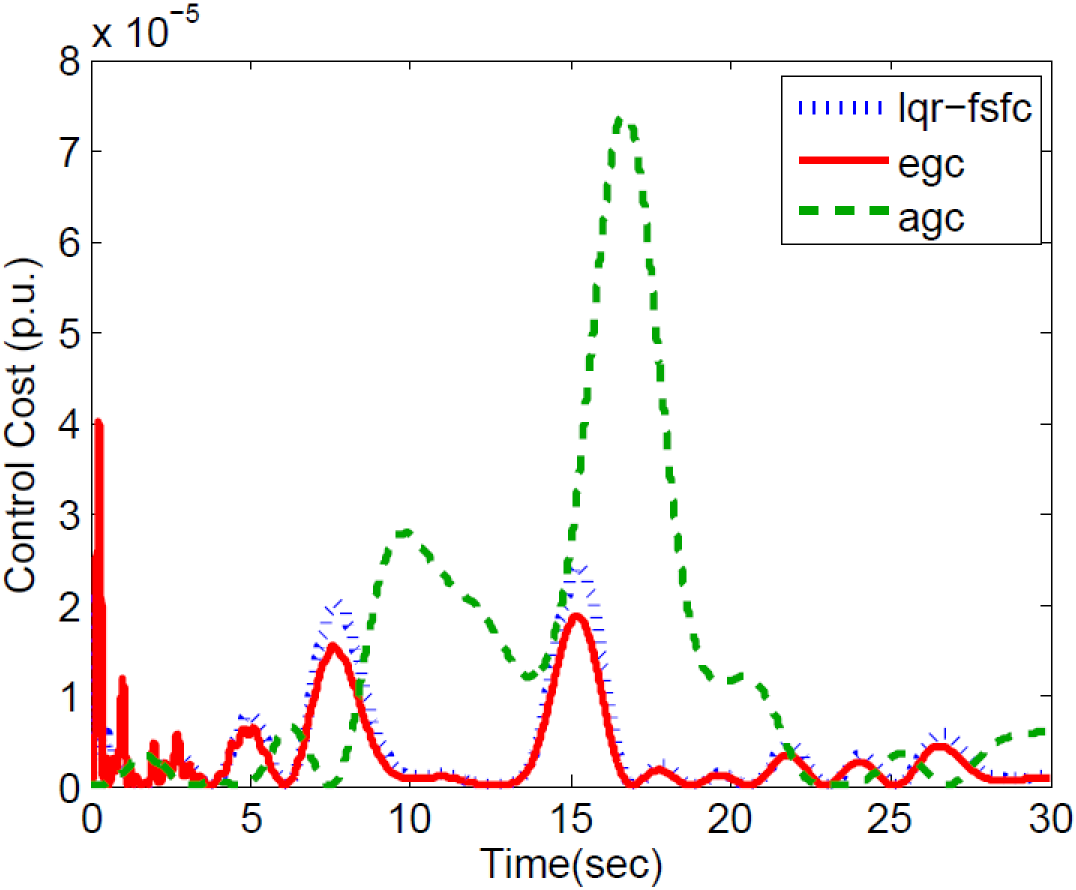


(c) AGC with Flywheel Only



(d) AGC with Diesel and Flywheel

Comparative Simulation Studies--Cost

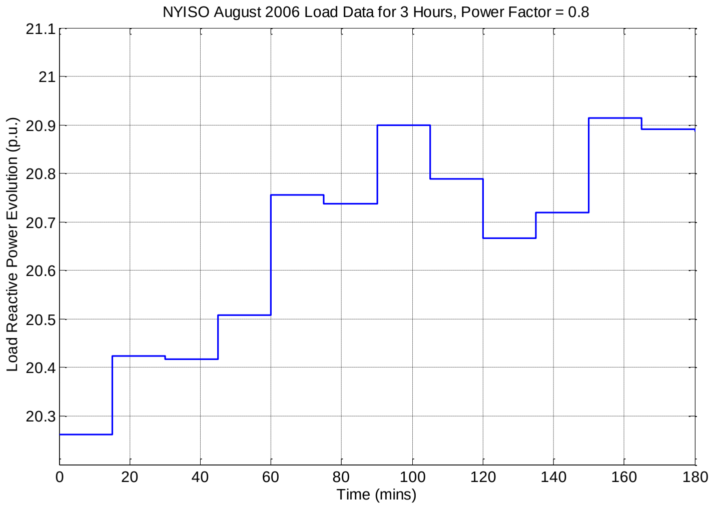


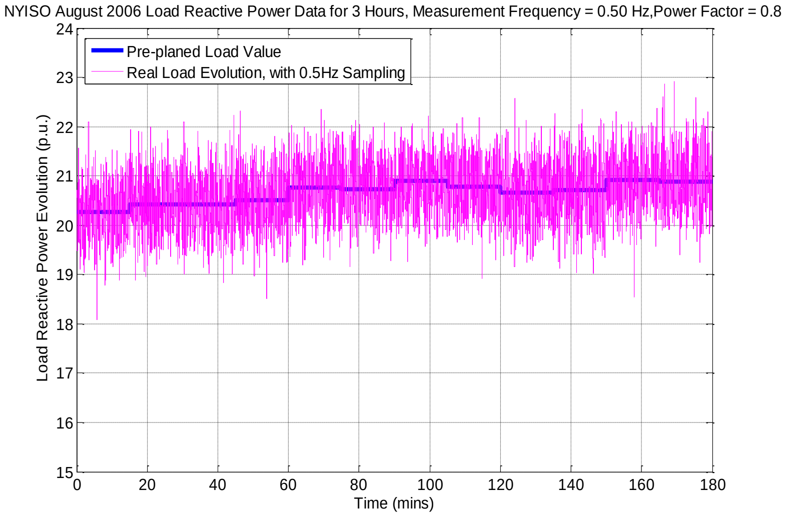
Remarks

- AGC costs much higher; E-AGC costs close to the LQR-based method
- The results suggest that E-AGC is the most practical and cost-effective among the compared frequency regulation methods

Issues with QoS for voltage

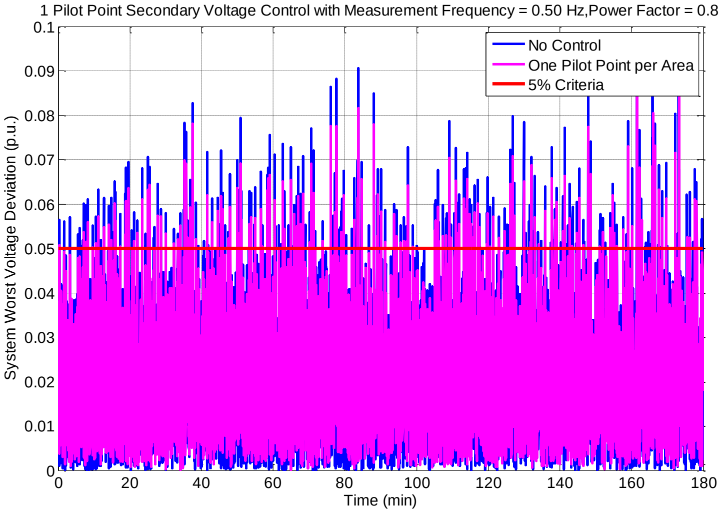
Scheduled load value and the disturbance around the value

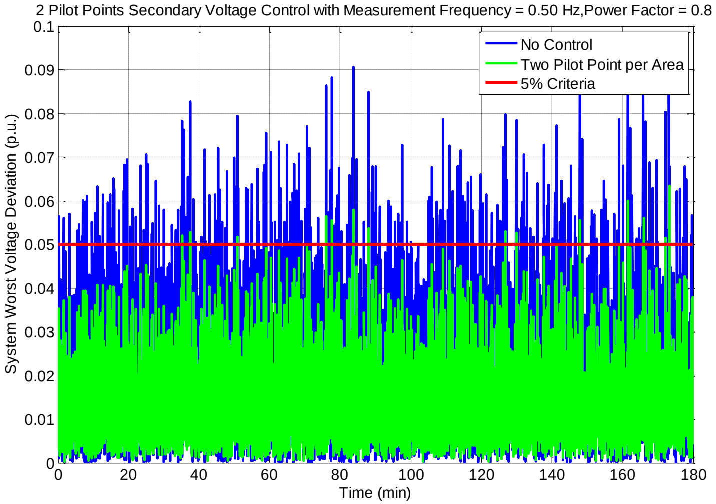




Automatic Voltage Control (AVC) VC for the NPCC with PMUs

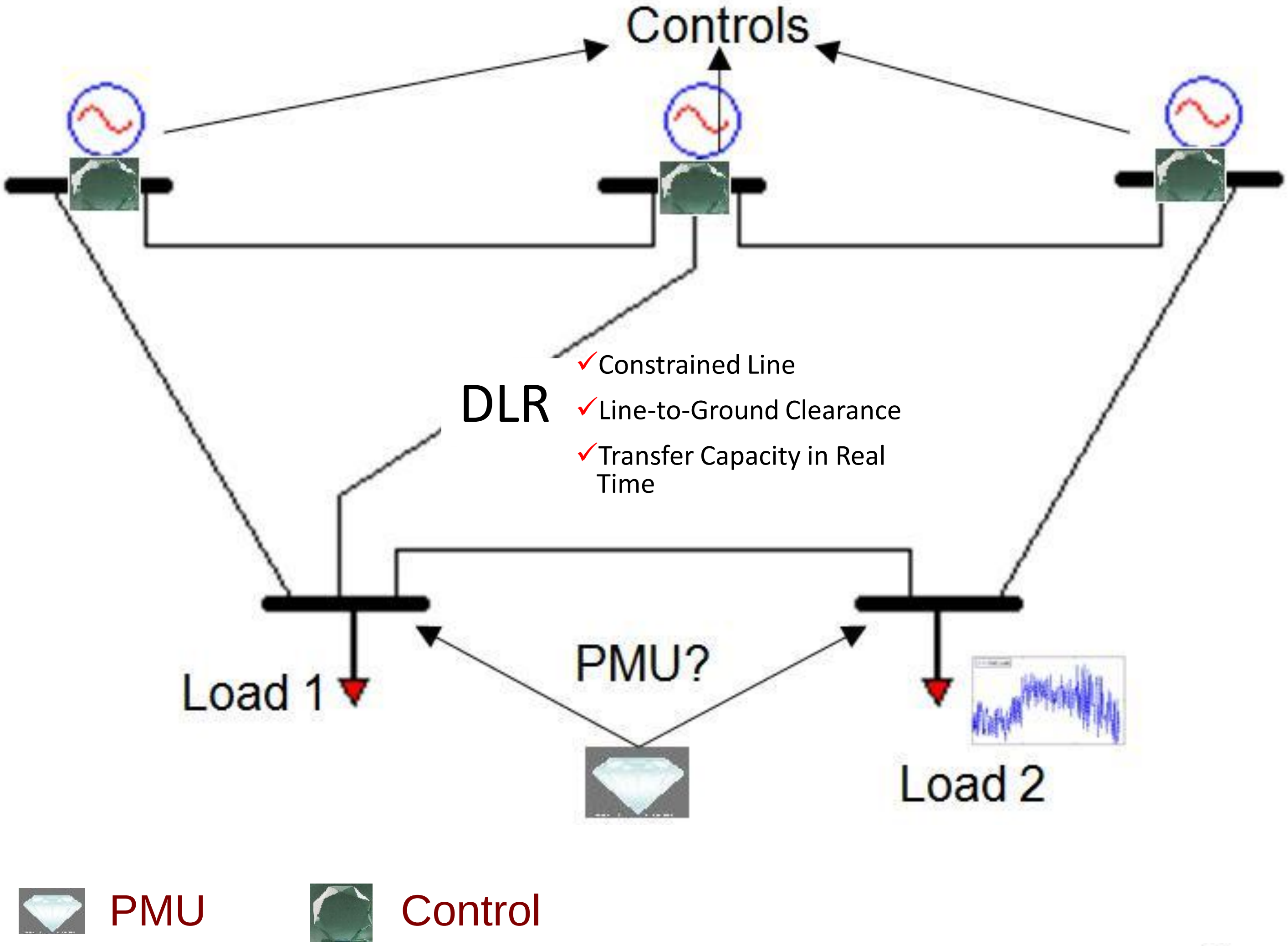
Simulations to show the worst voltage deviations in response to the reactive power load fluctuations (3 hours)


1 Pilot Point Secondary Voltage Control with Measurement Frequency = 0.50 Hz,Power Factor = 0.8


2 Pilot Points Secondary Voltage Control with Measurement Frequency = 0.50 Hz,Power Factor = 0.8

2 Pilot Points Control Performs Better Than 1 Pilot Point!

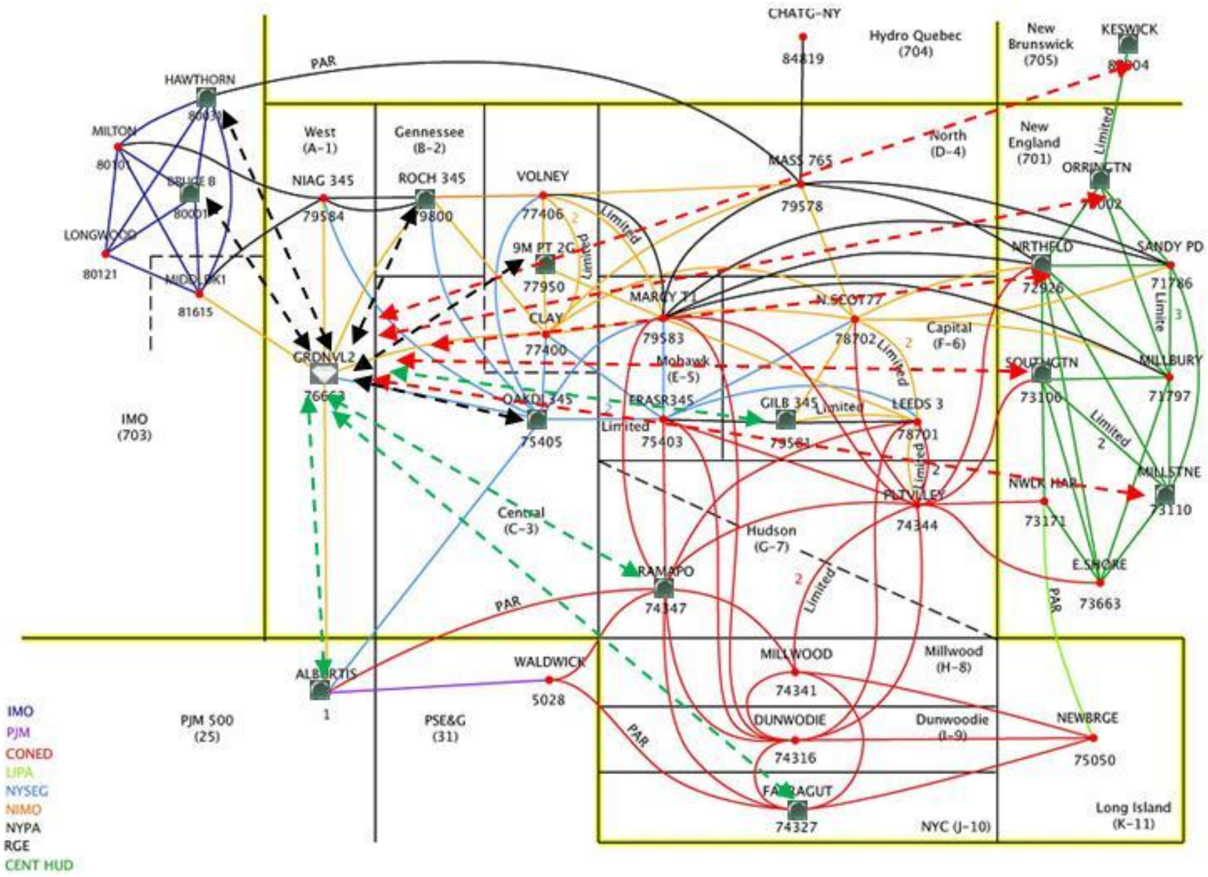
Use of on-line fast and accurate measurements—Future [12]



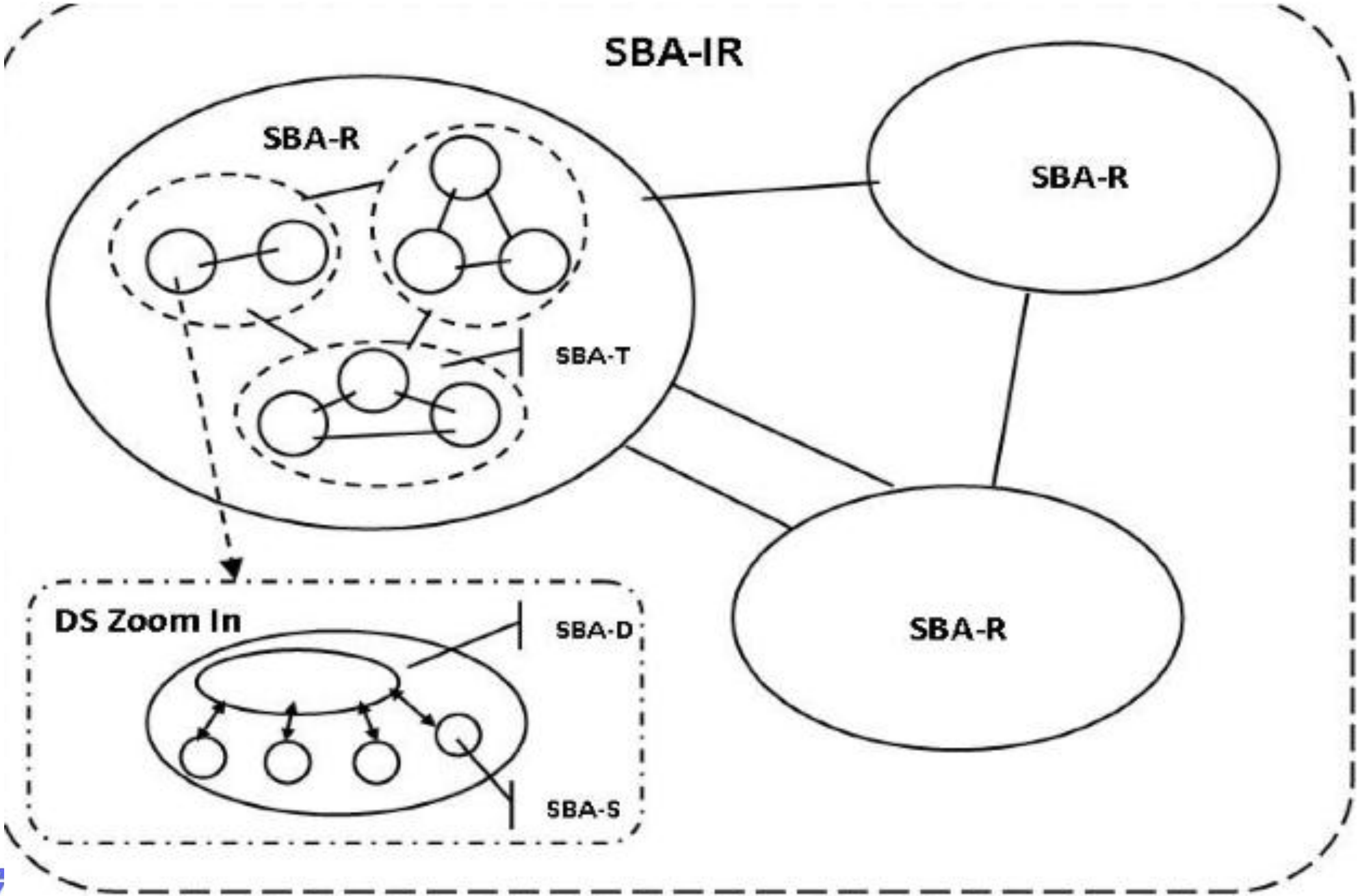
- ✓Constrained Line
- ✓Line-to-Ground Clearance
- ✓Transfer Capacity in Real Time

Northeastern Power Coordinating Council (NPCC) System

- ❑ Take NPCC system as *ONE AREA*; then put 1, 2 and 3 PMUs at pilot buses [13]



Multi-layered smart balancing authorities [14]



Concluding remarks

- Much progress toward distributed scheduling and congestion management
- Governance issues: Who manages the temporal and spatial risk? Implications on how much of distributed scheduling will be deployed.
- Need for large-scale scheduling algorithms under uncertainties, multi-temporal and multi-spatial constraints
- AN IMPORTANT NEW QUESTION: WHAT ARE THE OPTIMAL SCHEDULES TO MAXIMIZE POWER TRANSFERS IN ONTARIO WITHOUT COAL PLANTS
- Distributed control design a manageable challenge; huge opportunity for power-electronics controllers
- Need standards for dynamics

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