Carnegie Mellon

Electric Energy Systems Group

Electrical & Computer Engineering

Smart Grids
End-to-End Cyber Physical Systems (CPS) for Sustainable Socio-Ecological Energy Systems

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Acknowledgments

- This seminar is based on the collaborative work at Carnegie Mellon University's Electric Energy Systems Group (EESG), Ilic team. Over 10 graduate students are working on different aspects of Dynamic Monitoring and Decision Systems (DYMONDS) framework presented. The first proof—of-concept based on this framework can be found in the recently published book entitled
- Engineering IT-Enabled Sustainable Electricity Services: The Case of Low-Cost Green Azores Islands, co-edited by Ilic, Xie and Liu, Springer Publishers, 2013.

Importance of electric energy services

- Critical national infrastructure
- Huge part of US economy (>$200 billion business)
- Major source of carbon footprint
- Potential large user of cyber technologies
- Industrialized economy depends on low-cost electricity service

It works today, but…

- Increased frequency and duration of service interruption (effects measured in billions)
- Major hidden inefficiencies in today's system (estimated 25% economic inefficiency by FERC)
- Deploying high penetration renewable resources is not sustainable if the system is operated and planned as in the past (``For each 1MW of renewable power one would need .9MW of flexible storage in systems with high wind penetration" –clearly not sustainable)
- Long-term resource mix must serve long-term demand needs well

Huge opportunities and challenges

- Once in 50 years opportunity; progress/investments in hardware and small-scale pilot demonstrations
- New physical architectures evolving; the old top-down operating and planning approach won't work; one size no longer fits all
- Cyber architectures trailing behind; one size doesn't fit all but possible to have a unifying framework with common design principles
- From grid-centric to secure cooperative user-centric

One possible unifying view: Sustainable Socio-Ecological Systems (SES)

- Builds on the work of Elinor Ostrom for sustainable water systems
- Several key points

-characteristics of core variables in an SES determine how sustainable the system is

-several qualitatively different SES (second order variables)

-deeper-order variables (interactions) between the core variables determine what is needed to make the SES more sustainable

The role of man-made CPS in enhancing sustainability of an SES

- Basic SES
- Modeling for sustainability meets modeling for CPS design
- Relating deeper-level interaction variables to physics- and economic interaction variables
- Future grid: end-to-end CPS enabling best possible sustainability of a given SES
- We take this as the basis for establishing common unifying principles of designing CPS in future power grids

Making the most out of the naturally available resources?

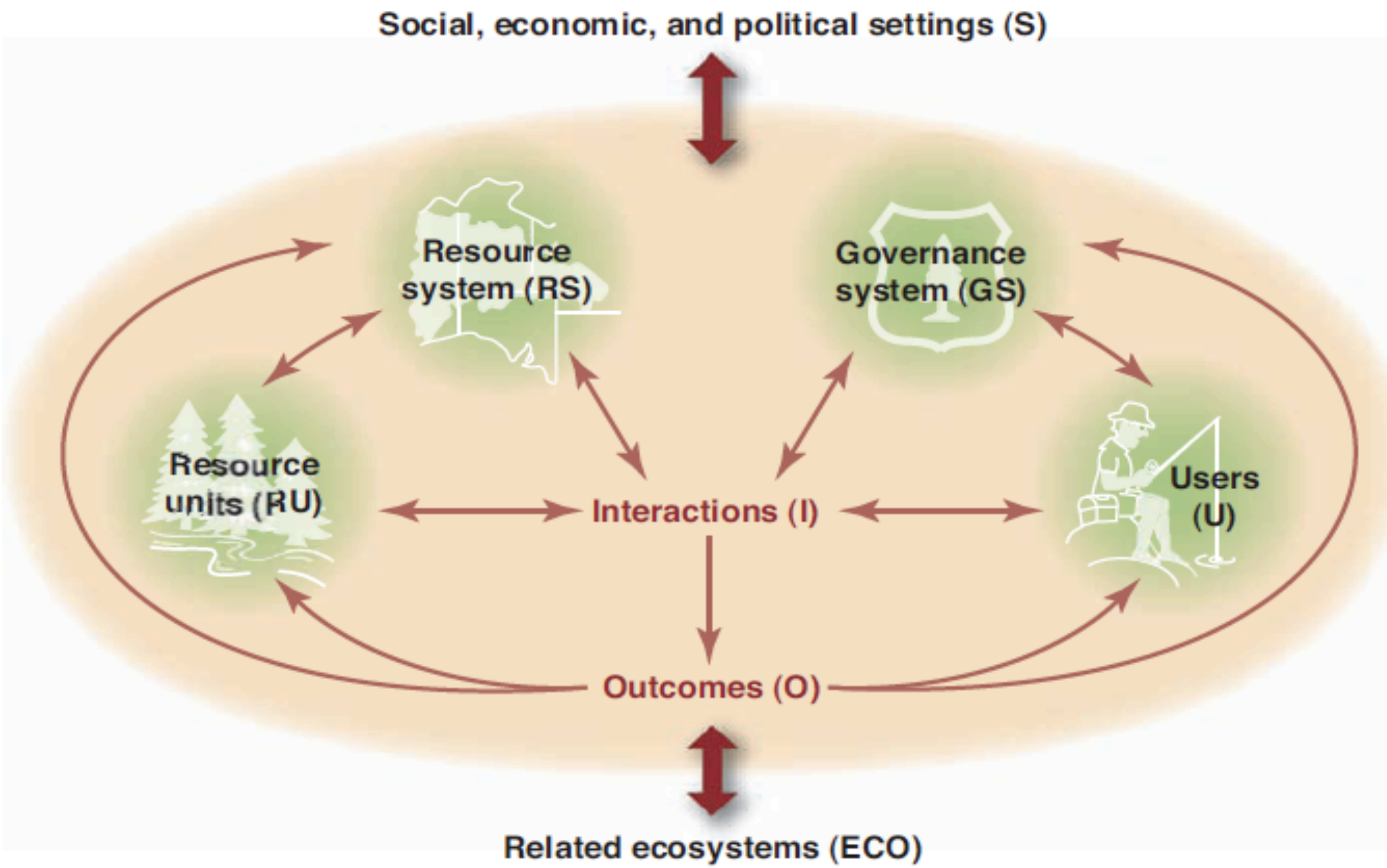


Fig. 1. The core subsystems in a framework for analyzing social-ecological systems.

"Smart Grid" ←→ electric power grid and IT for sustainable energy SES

Energy SES	Man-made Grid	Man-made ICT
• Resource system (RS) • Generation (RUs) • Electric Energy Users (Us)	• Physical network connecting energy generation and consumers • Needed to implement interactions	• Sensors • Communications • Operations • Decisions and control • Protection

An illustrative future system

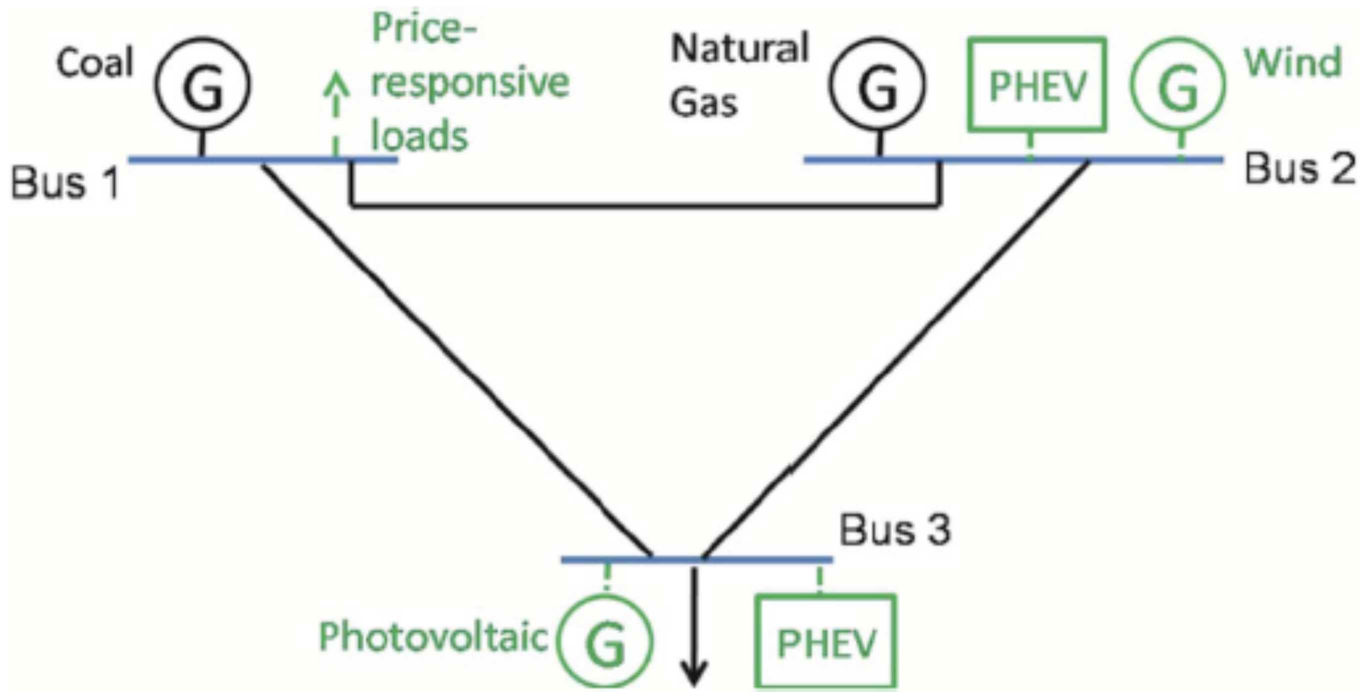


Fig. 5. Small example of the future electric energy system.

Must proceed carefully…

- The very real danger of new complexity.
- Technical problems at various time scales lend themselves to the fundamentally different specifications for on-line data, models and cyber design
- No longer possible to separate measurements, communications and control specifications
- Major open question: WHAT CAN BE DONE IN A DISTRIBUTED WAY AND WHAT MUST HAVE FAST COMMUNICATIONS

The need for more detailed CPS

- Not a best effort problem; guaranteed performance
- Multi-physics, multi-temporal, multi-spatial, multi-contextual dynamic system; nonlinear dynamics
- Complex time-space scales in network systems (milliseconds—10 years; one town to Eastern US)
- Inadequate storage
- Large-scale optimization under uncertainties
- Complex large-scale dynamic networks (energy and cyber)
- Information and energy processing intertwined
- Framework required for ensuring guaranteed performance

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

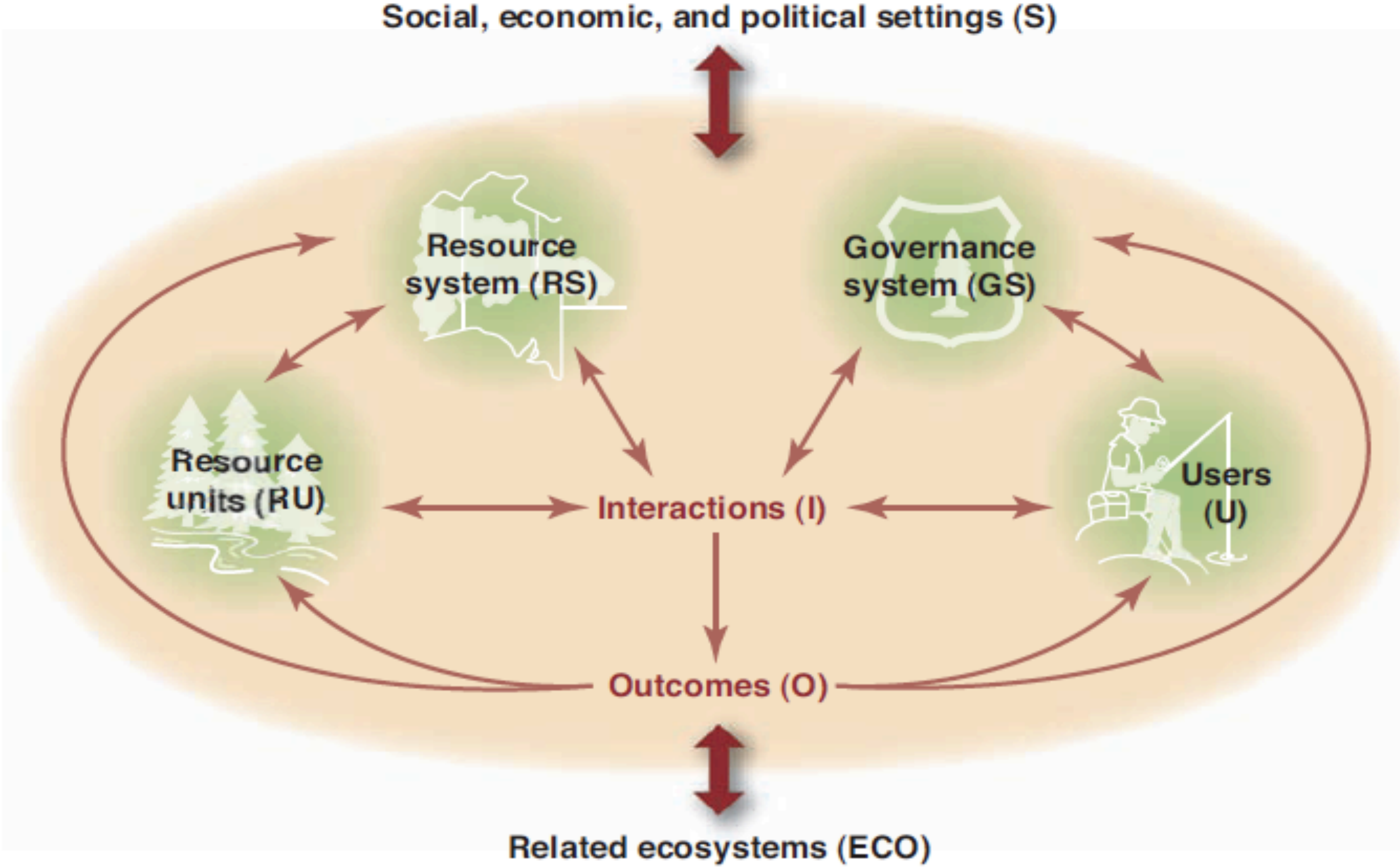
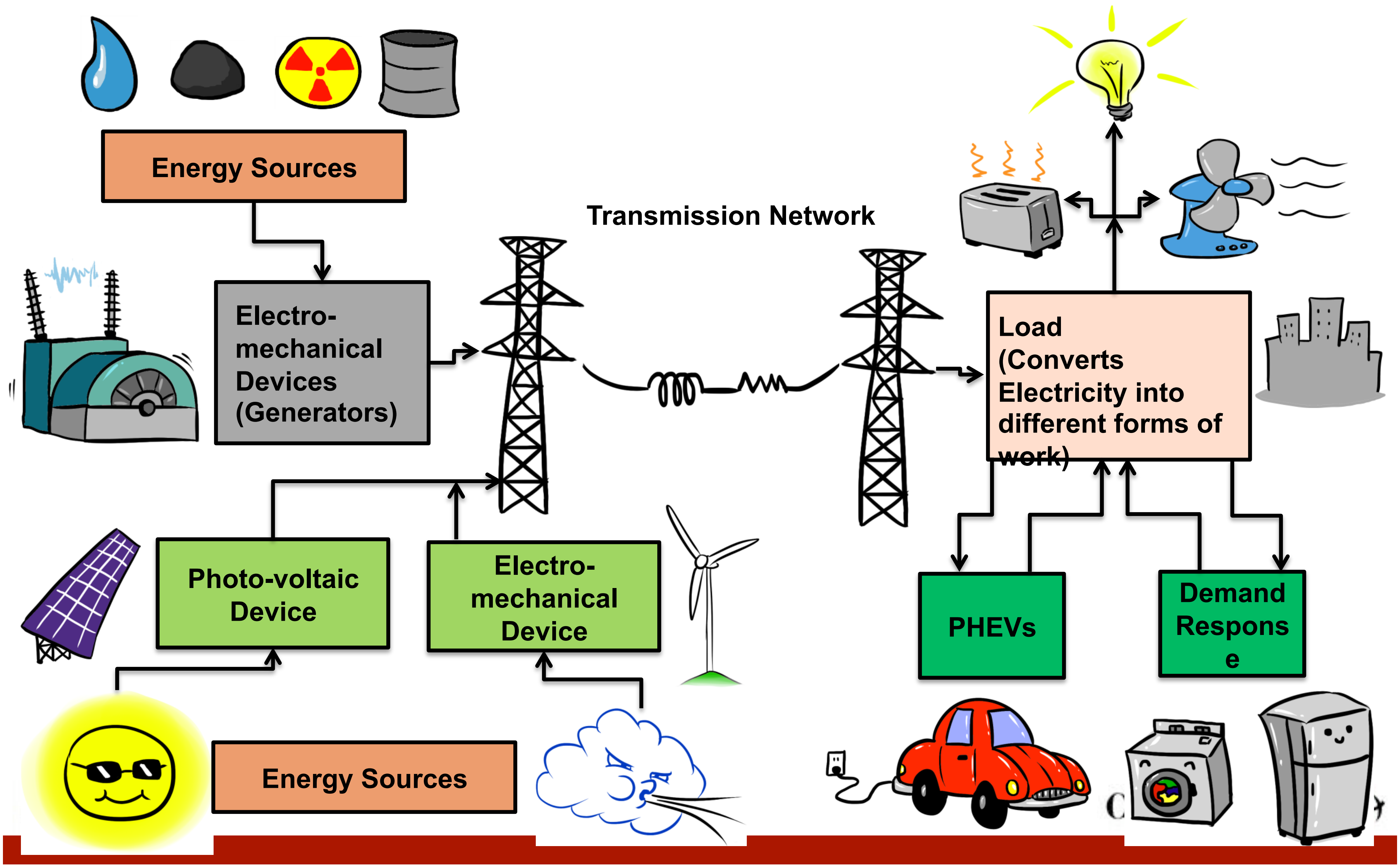
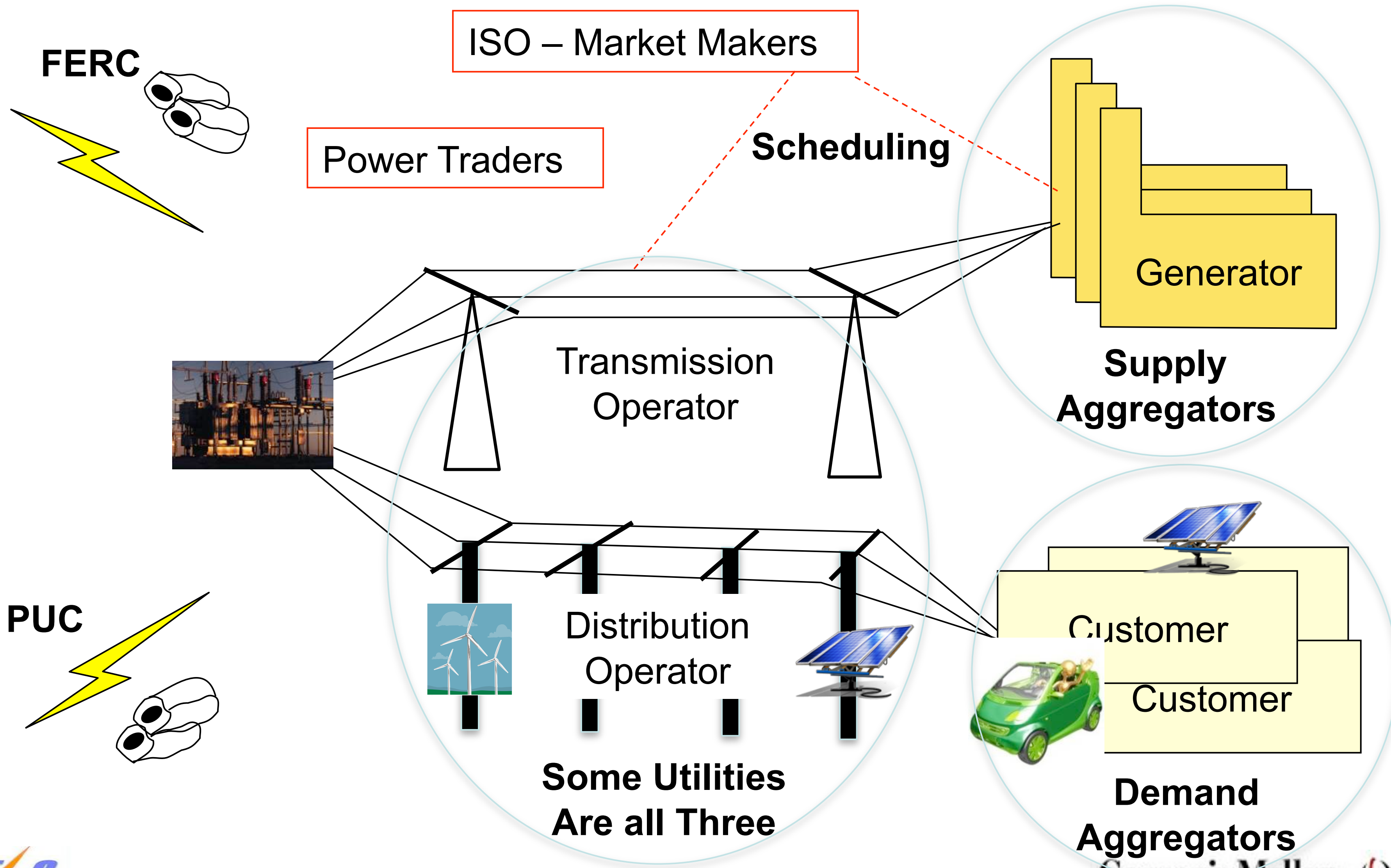


Fig. 1. The core subsystems in a framework for analyzing social-ecological systems.

Future Power Systems-Diverse Physics



Contextual complexity



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]	—

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

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

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

Complexity of interconnected electric energy systems

- Determined by the complex interplay of component dynamics (resources and demand); electrical interconnections in the backbone grid and the local grids; and by the highly varying exogenous inputs (energy sources, demand patterns)
- Renewable resources are stochastic
- The actual demand is stochastic and partially responsive to system conditions
- Multi-physics,multi-temporal,multi-spatial,multi-contextual

"Smart Grid" ←→ electric power grid and ICT for sustainable energy systems

Core Energy Variables	Man-made Grid	Man-made ICT
• Resource system (RS) • Generation (RUs) • Electric Energy Users (Us)	• Physical network connecting energy generation and consumers • Needed to implement interactions	• Sensors • Communications • Operations • Decisions and control • Protection • Needed to align interactions

Five qualitatively different physical power grids

Bulk Electric Energy Systems -Regulated	Bulk Electric Energy Systems -Restructured	Hybrid Electric Energy Systems	Fully Distributed Electric Energy Systems— Developed Countries	Fully Distributed Electric Energy Systems- Developing Countries

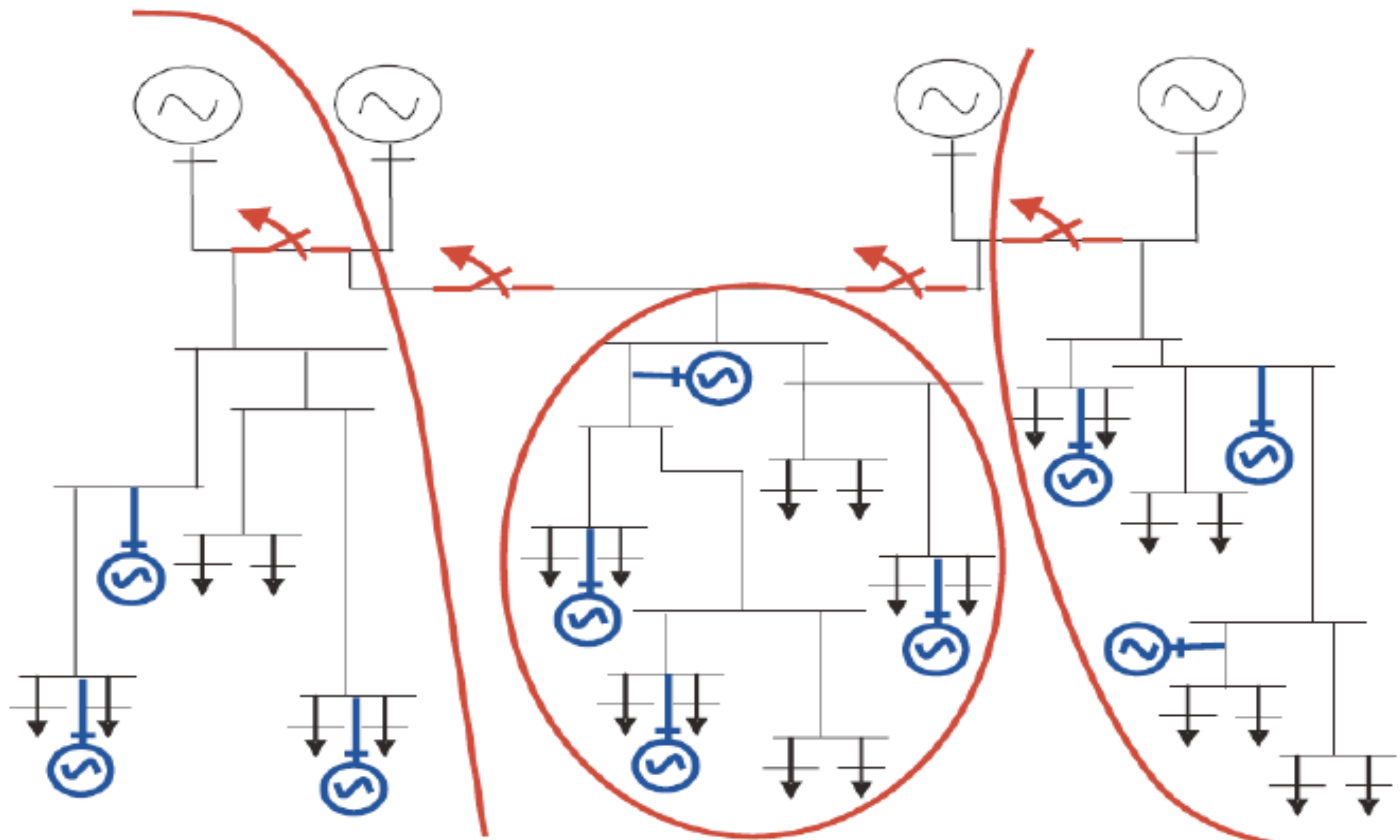
IT-enabled smarter energy systems

- Given physical energy systems, how to design the grid infrastructure and the cyber overlay to make the most out of naturally available resources?
- Complex systems engineering problem (temporal, spatial, contextual)
- The main challenge: What information should be collected/processed/exchanged to minimally coordinate the multi-layered physical system for provable performance?

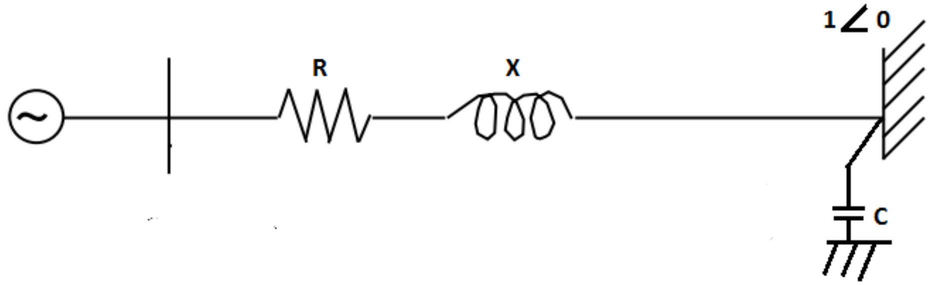
The challenge of designing CPS for SEES

- Must be done with careful accounting of the underlying SEES
- Modeling and problem posing– based on the basic ECE disciplines!
- Dynamical systems view of today's and future electric energy systems.
- 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.
- One size cyber solution does NOT fit all; but the same interactions variables-based framework can be used—Dynamic Monitoring and Decision Systems (DYMONDS)

Bulk regulated power grids



Linear Electromechanical Model



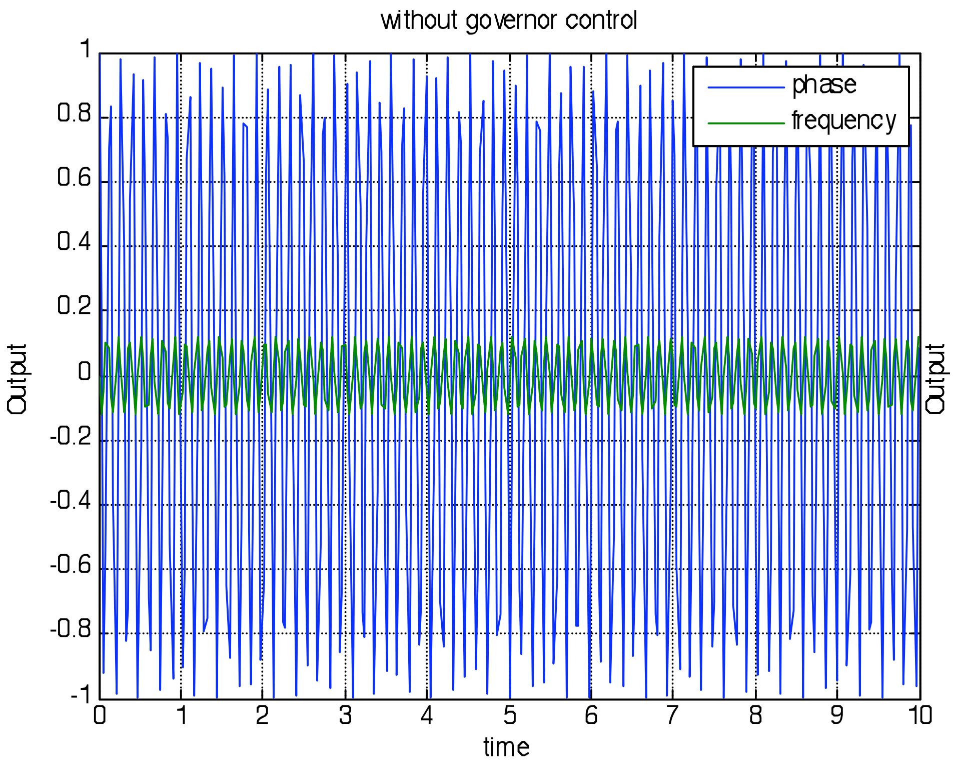
- System Model:

$$\begin{cases} \dot{\theta} = w_0 w \\ \dot{w} = -\frac{V_1 B}{J}\theta - \frac{D_d}{J} w \end{cases}$$

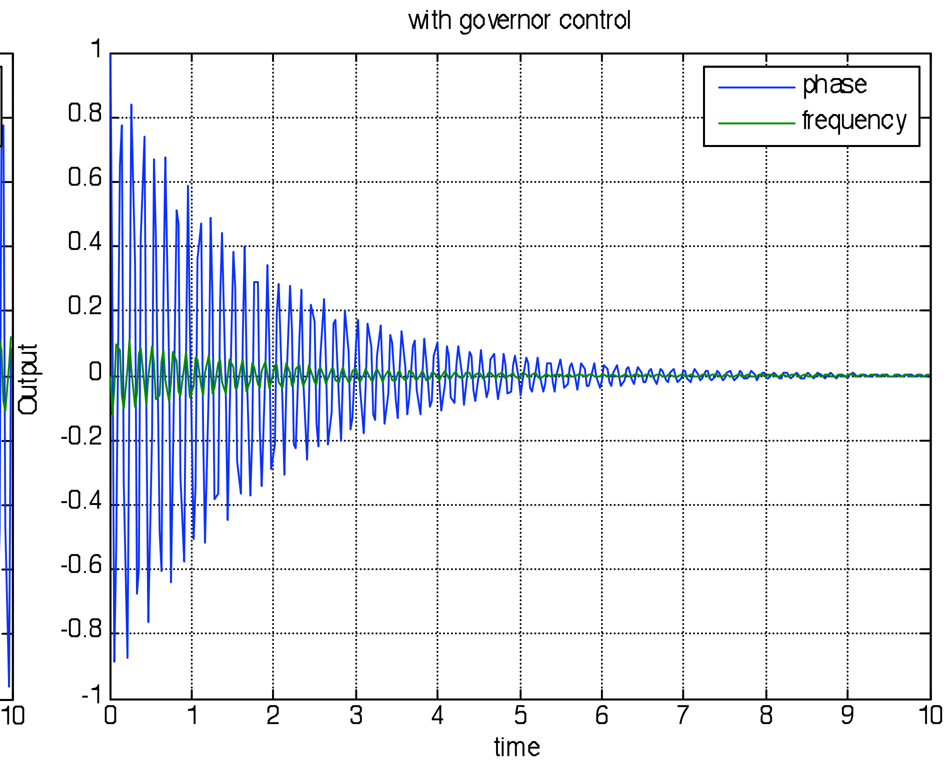
- Parameters:

$$w_0 = 2\pi f \quad f = 60\ Hz$$
$$R = 0.04 \quad X = 0.04$$
$$Z = R + jX \quad Y = \frac{1}{Z} = G + jB$$
$$J = 1.13 \ - \ inertia$$
$$\mathrm{D_d} - damping$$

With/without Damping(Governor)



$$D_d = 0$$
$$\lambda(A_{closed}) = 0 \pm 91.325i$$



$$D_d = 1$$
$$\lambda(A_{closed}) = -0.44 \pm 91.325i$$

Note: Matlab Function: ss() & lsim()

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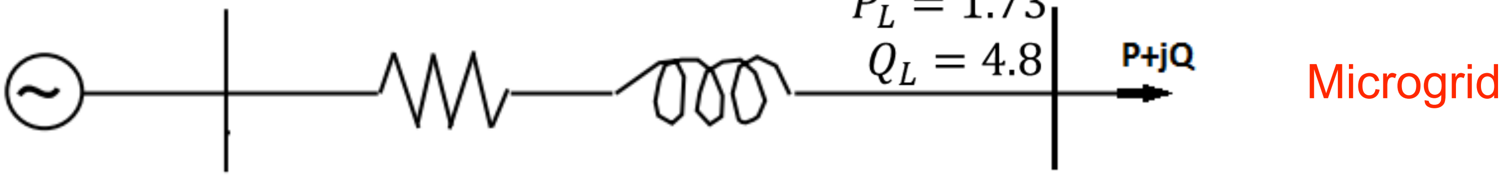
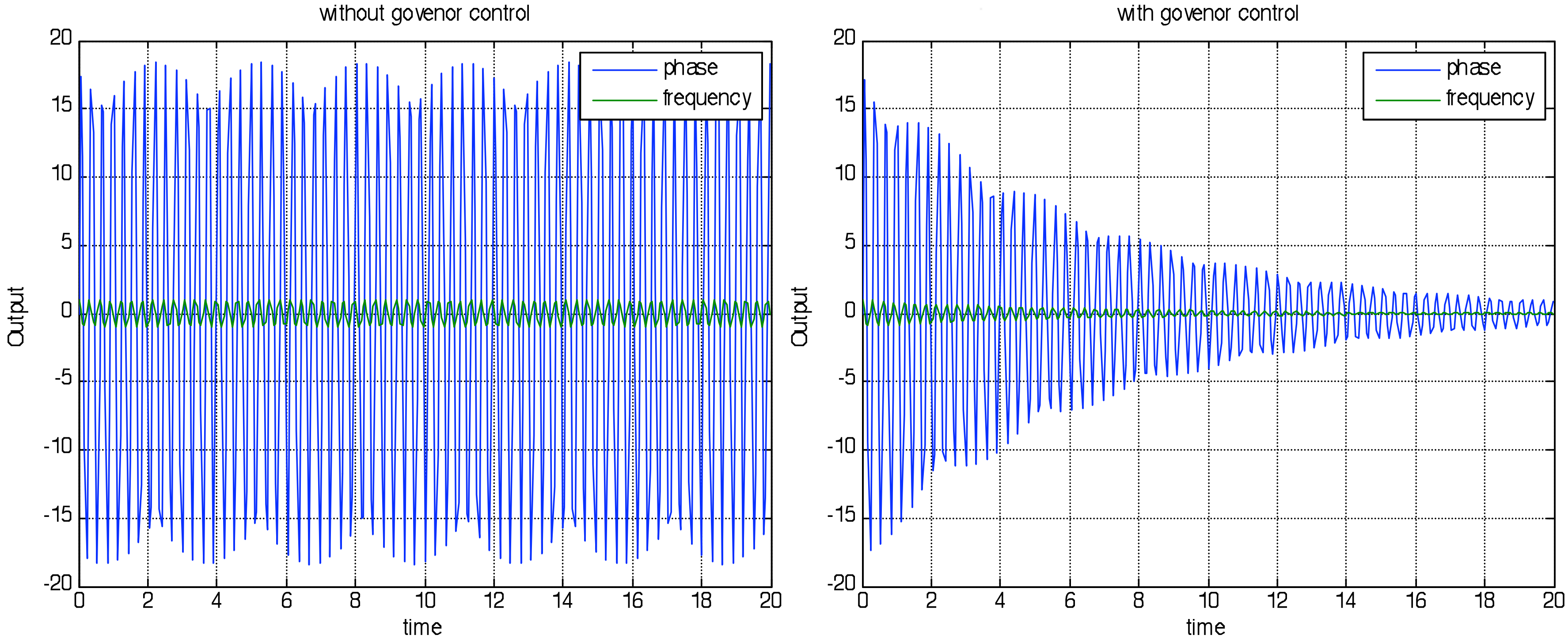
Constant power (case 1)



$P_L = 1.73$
$Q_L = 4.8$



$V_2 = 1.07$
$\theta_2 = 0.1556\, rad$

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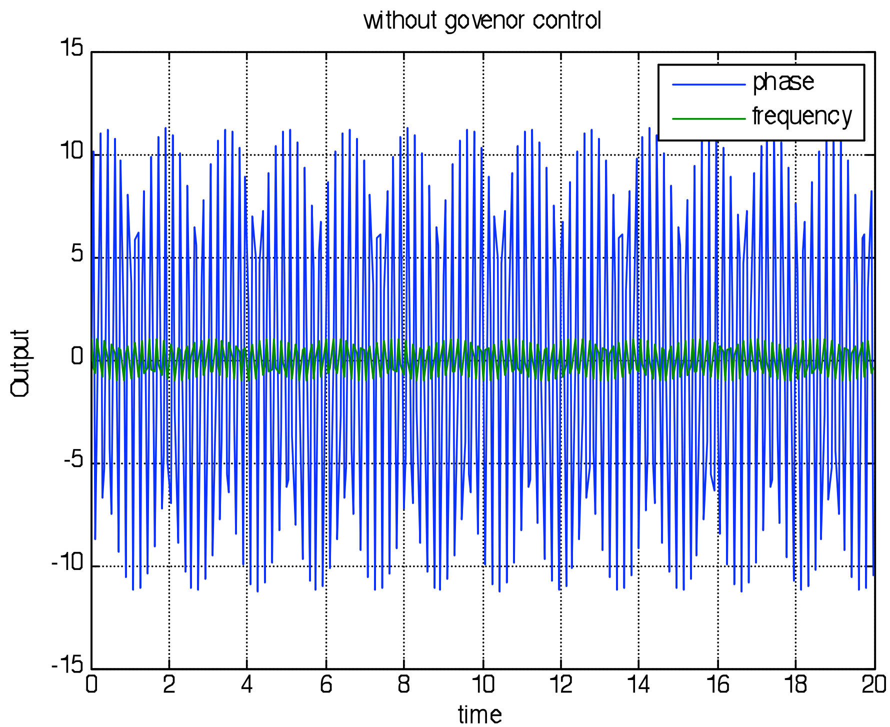
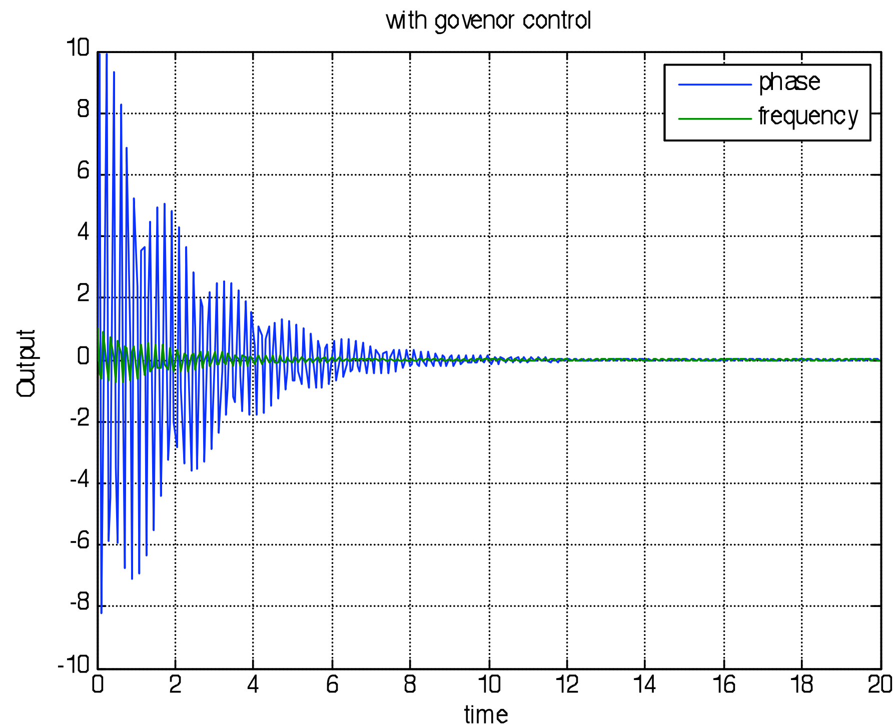
Constant power (case 2)

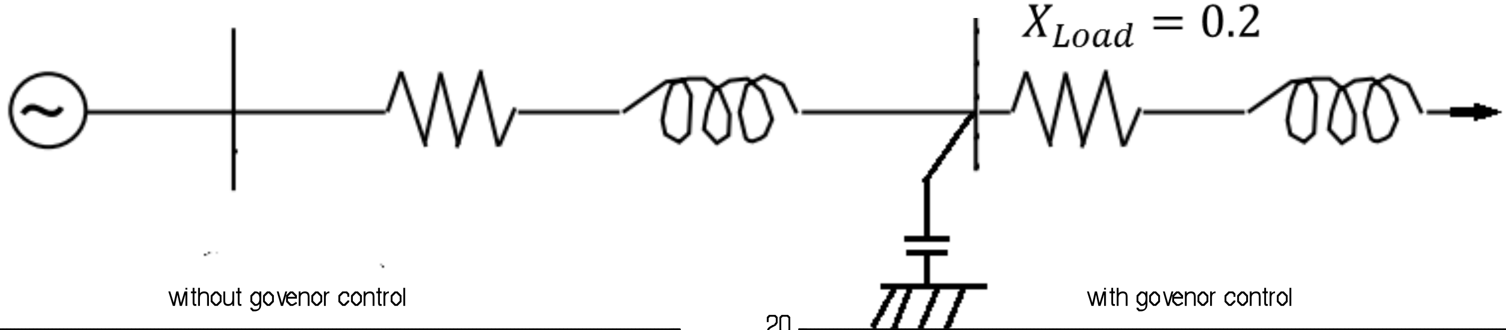


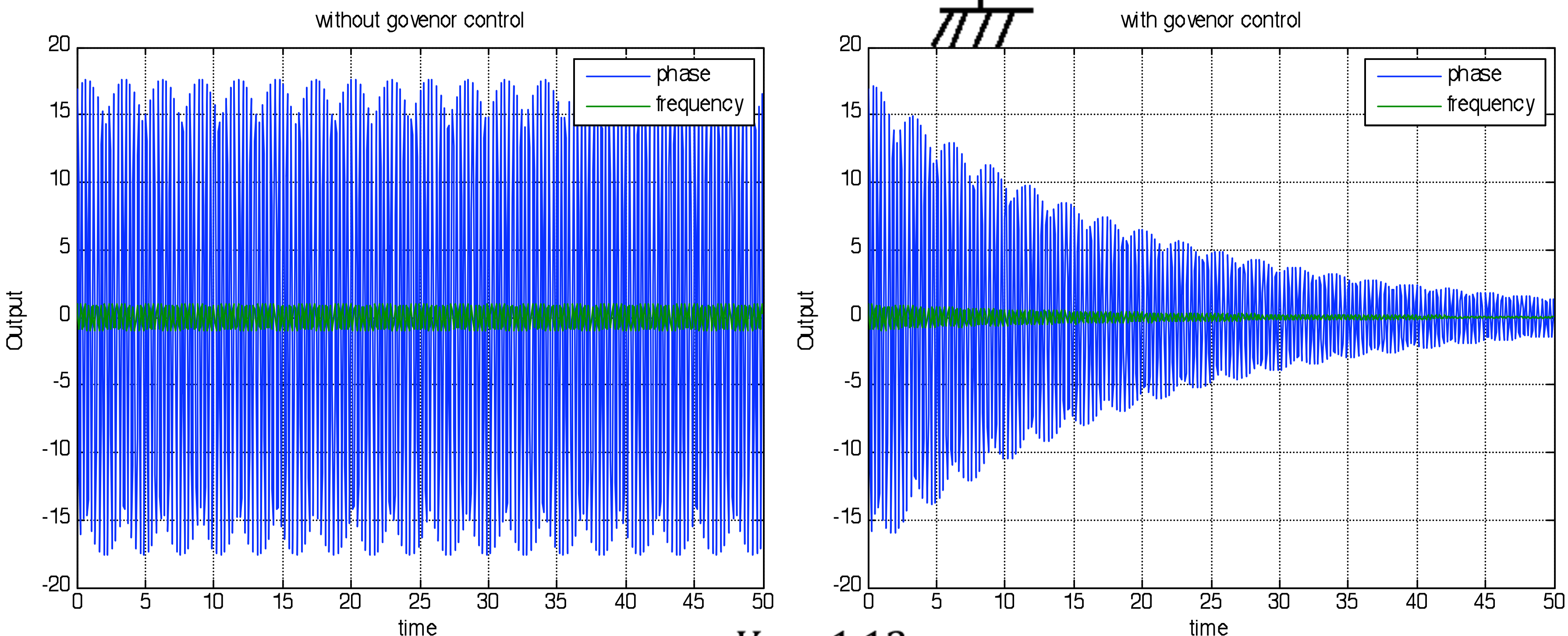


$$V_2 = 0.362$$
$$\theta_2 = 0.614\,rad$$

Constant Impedance

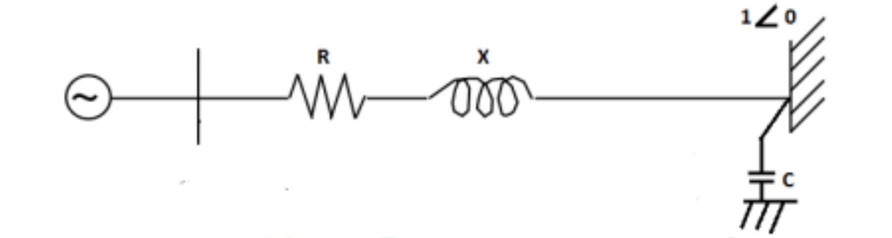
$R_{Load} = 0.003$
$X_{Load} = 0.2$





$V_2 = 1.12$
$\theta_2 = 0.256\,rad$

Nonlinear Model



System:

Note: Parameters come from Flores Island : (Diesel Power Plant -Chapter 16)

$$\begin{cases} \dot{\theta} = w_0(w - w^*) \\ \dot{w} = \frac{1}{M}(P_M - (e_q' i_q') - D(w - w_0)) \\ \dot{e_q}' = \frac{1}{T_{do}'}(-e_q' - (x_d - x_d)i_d + e_{fd} \end{cases}$$

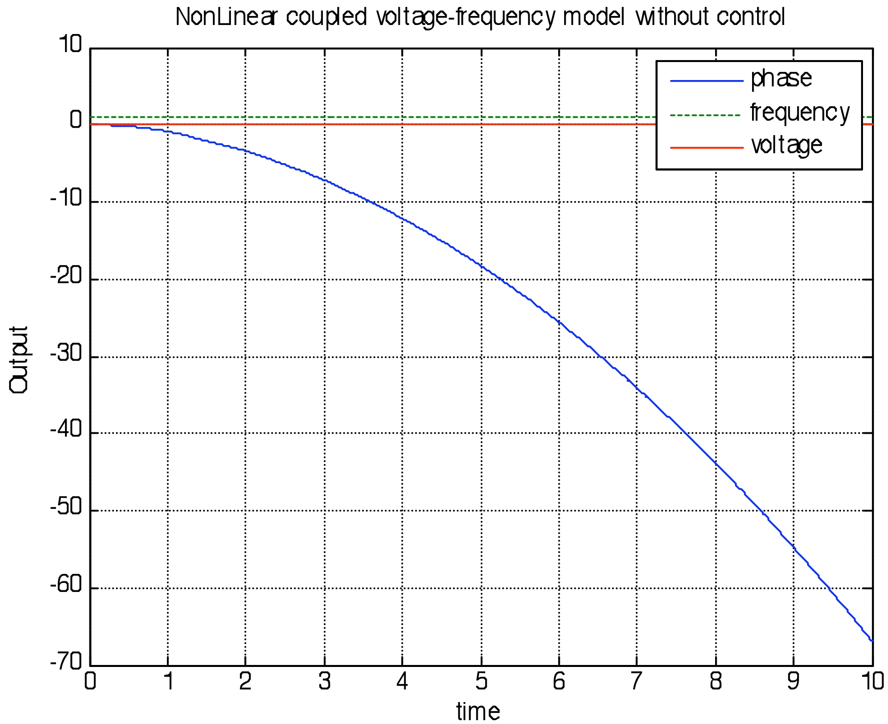
With AVR:

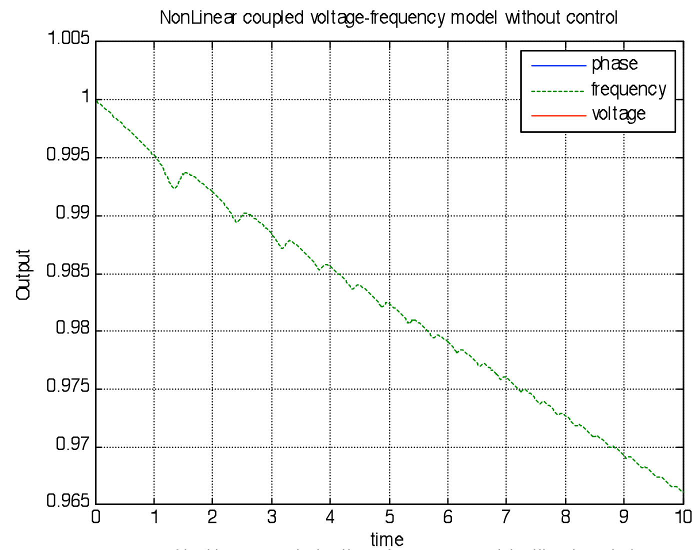
$$\begin{cases} \dot{\theta} = w_0(w - w^*) \\ \dot{w} = \frac{1}{M}(P_M - (e_q' i_q') - D(w - w_0)) \\ \dot{e_q}' = \frac{1}{T_{do}'}(-e_q' - (x_d - x_d)i_d + e_{fd} \\ \dot{V}_R = \frac{1}{T_A}(K_A V_F - \frac{K_A V_F}{T_F} e_{fd} - V_R - K_A E_t + K_A E^{ref}) \\ \dot{e_{fd}} = \frac{1}{T_E}(-(K_e + S_e)e_{fd} + V_R) \\ \dot{V}_F = \frac{1}{T_F}(-V_F + \frac{K_F}{T_F}\dot{e_{fd}}) \end{cases}$$

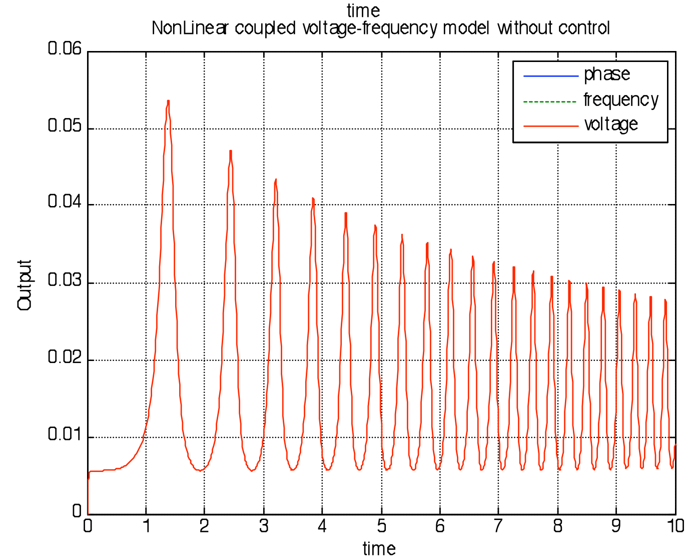
With Governor:

$$\begin{cases} \dot{\theta} = w_0(w - w^*) \\ \dot{w} = \frac{1}{M}(P_M - (e_q' i_q') - D(w - w_0)) \\ \dot{e_q}' = \frac{1}{T_{do}'}(-e_q' - (x_d - x_d)i_d + e_{fd} \\ \dot{P}_M = \frac{1}{T_u}(-P_M + K_t a) \\ \dot{a} = \frac{1}{T_g}(-ra - (w - w^{ref}) \end{cases}$$

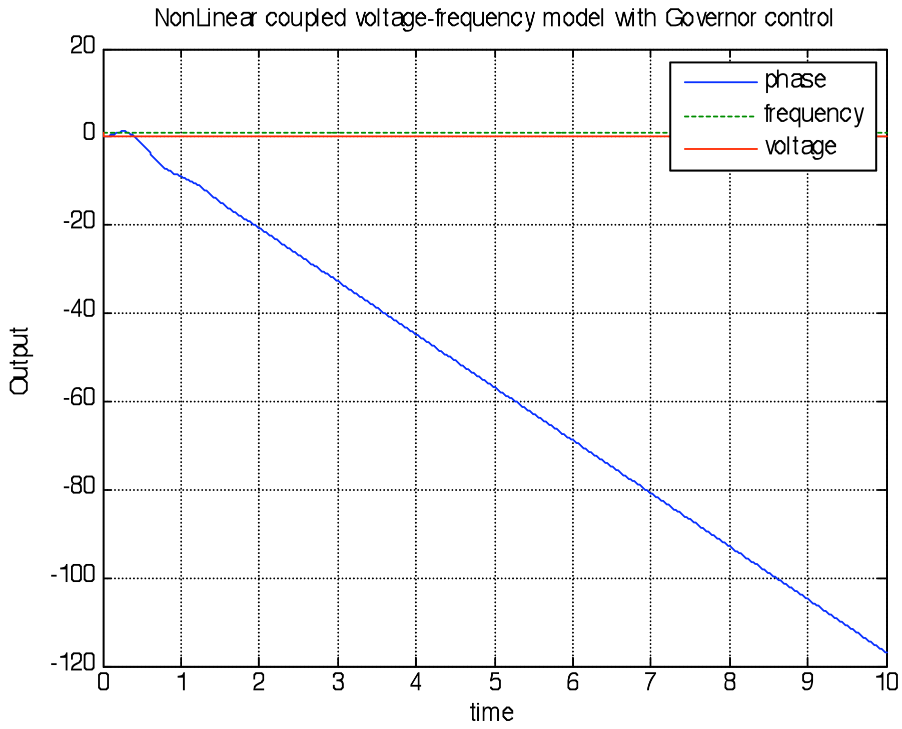
Without Control

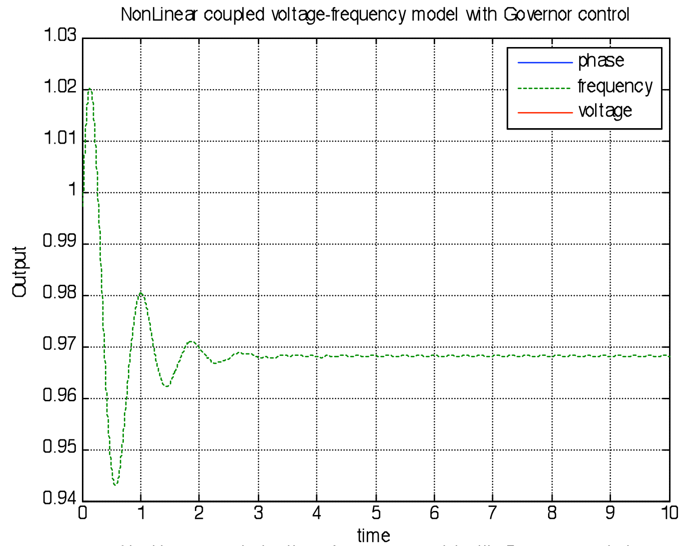


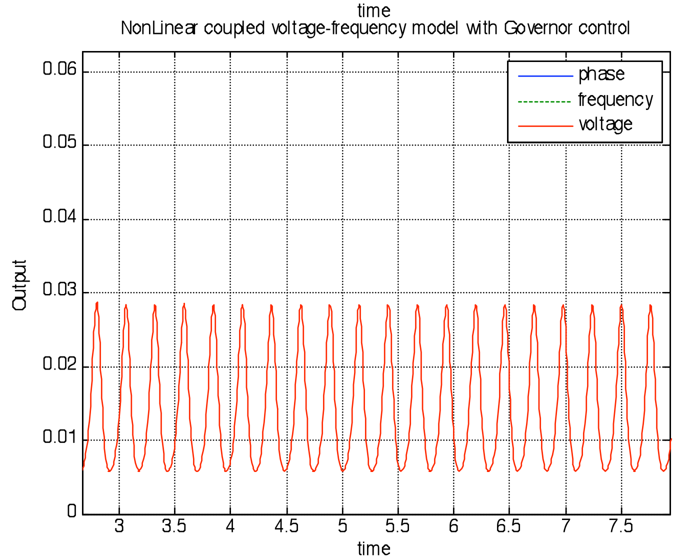




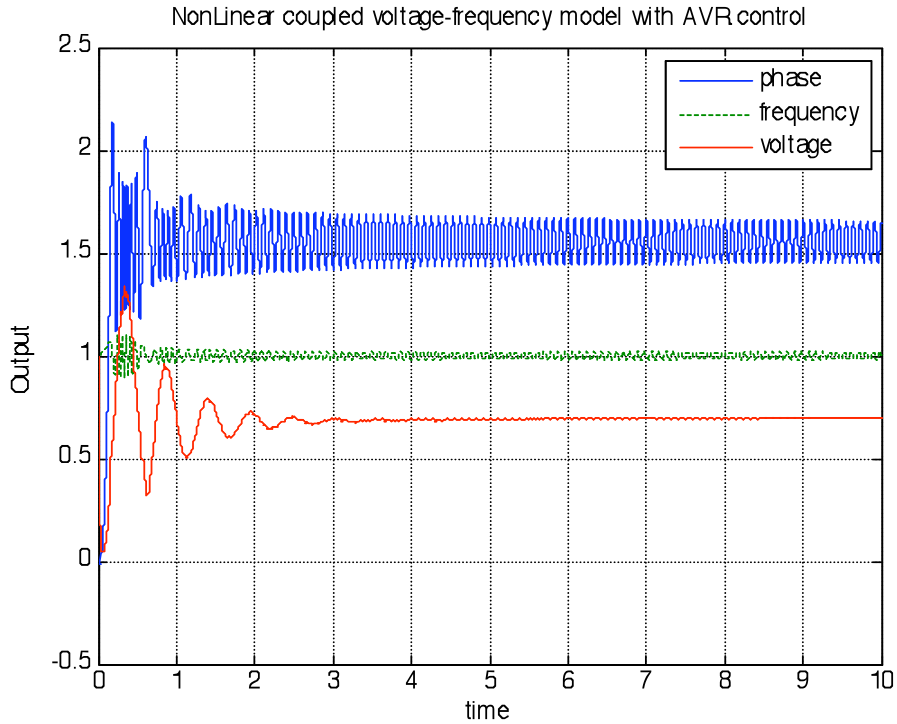
With Governor Control

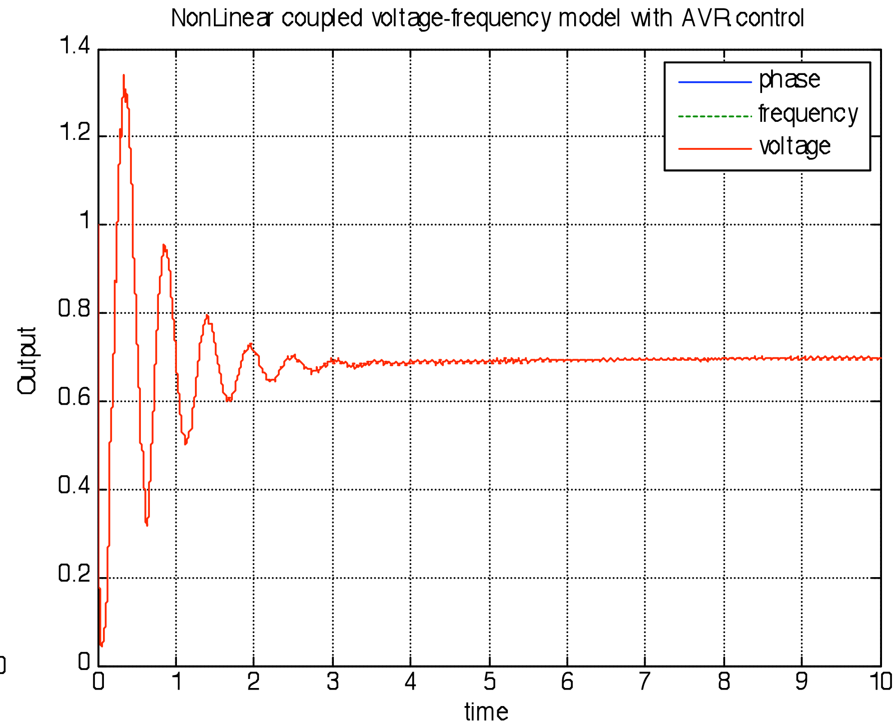






With AVR





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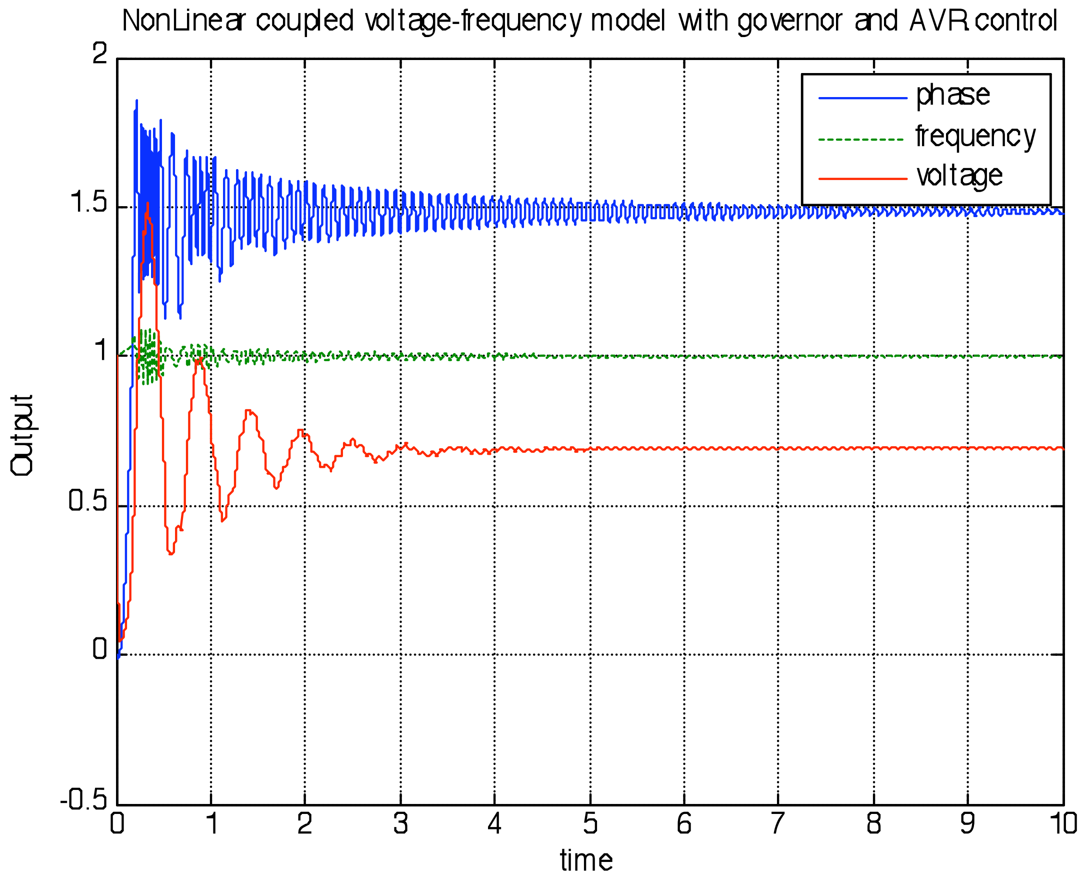
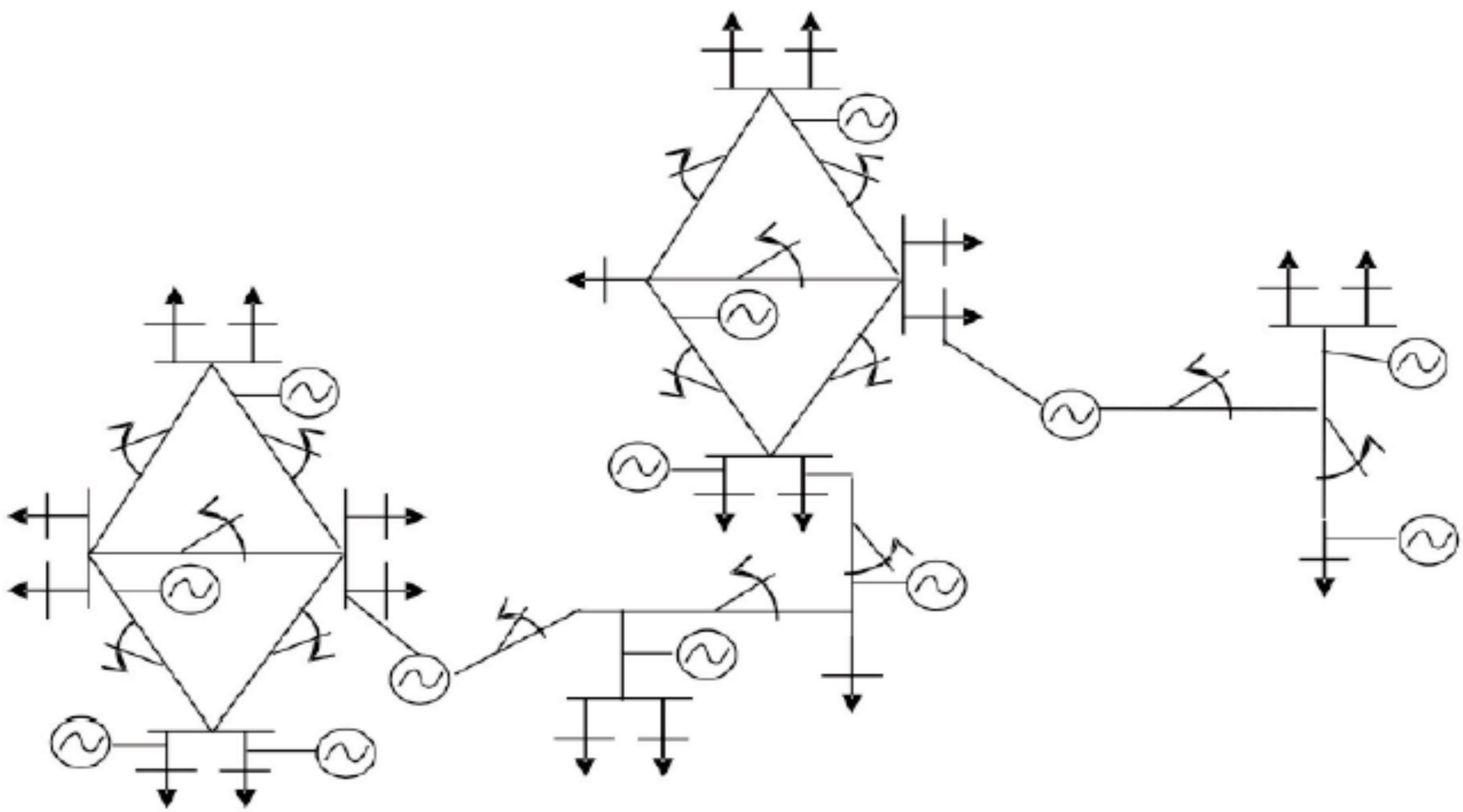
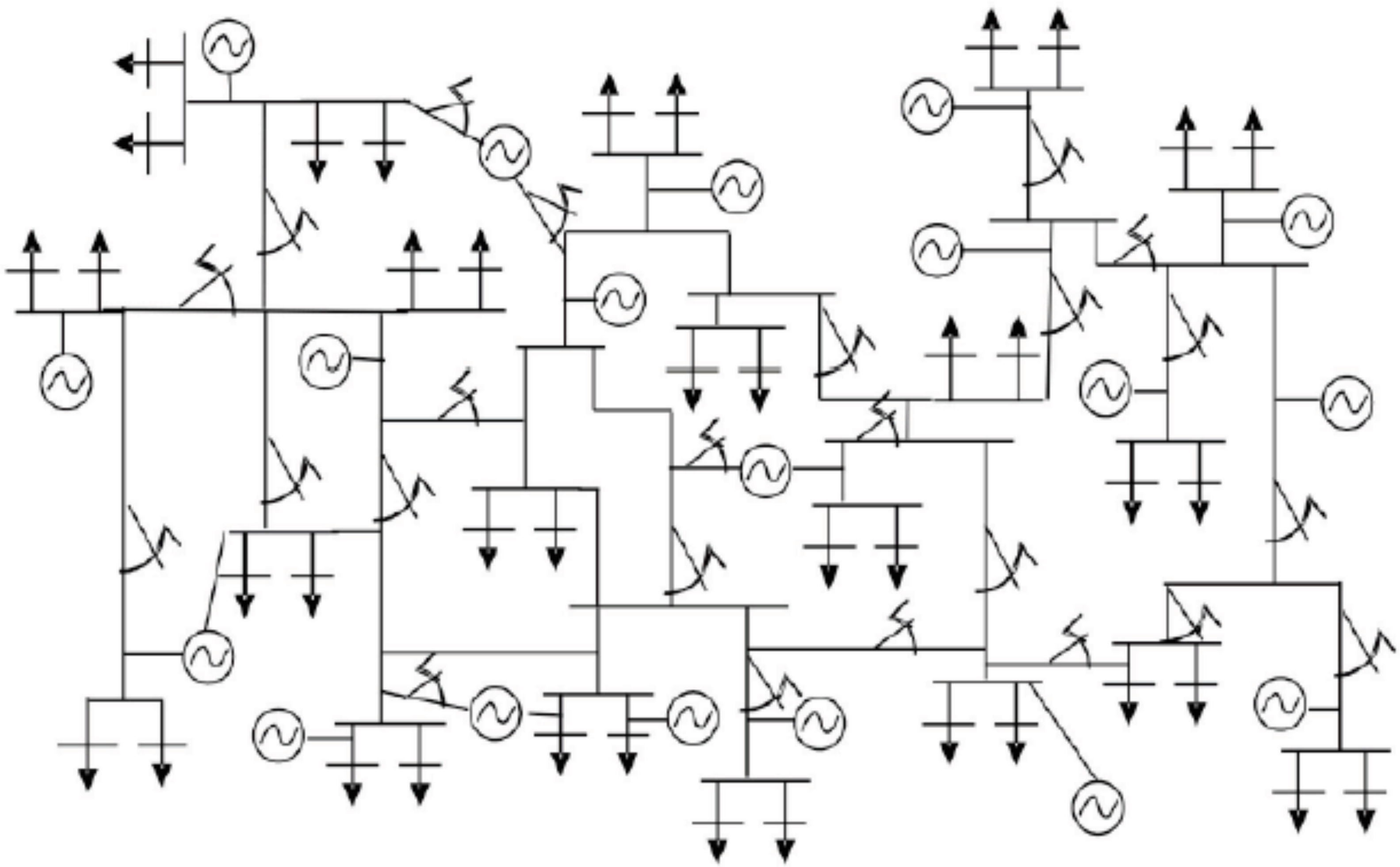
With AVR and Governor control



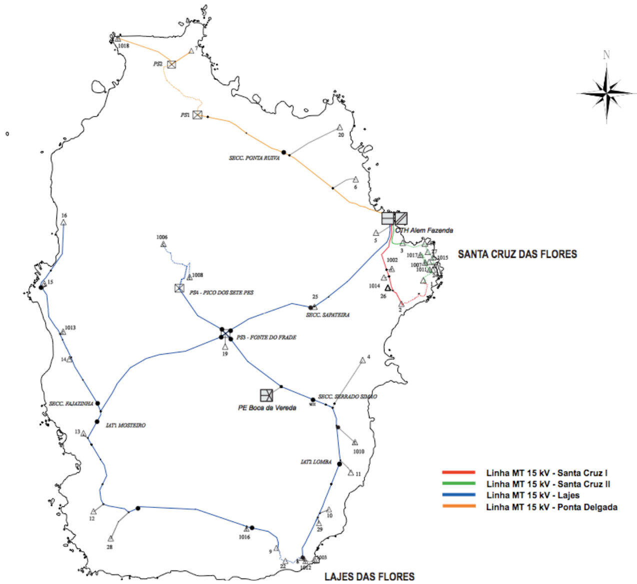
Hybrid Electric Energy System



Fully distributed small-scale systems

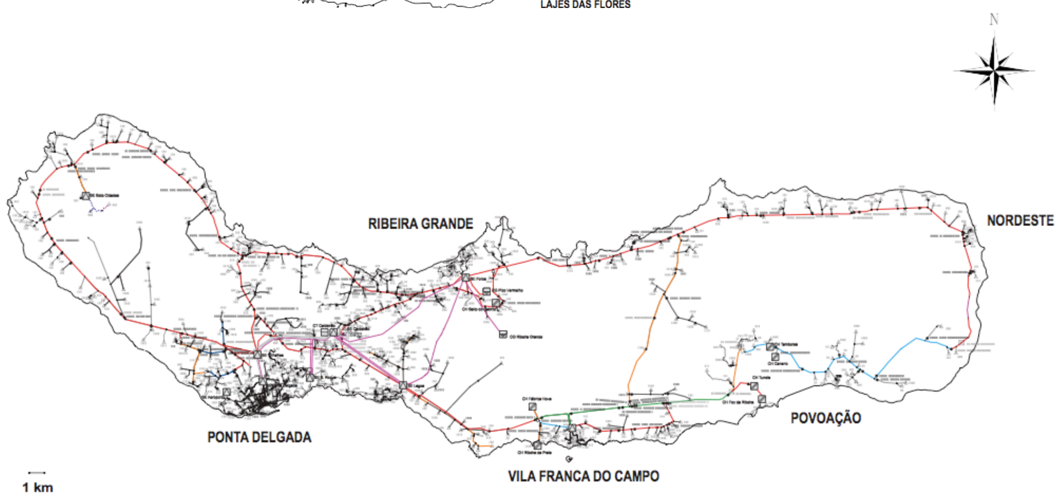


AZORES ISLAND: ELECTRICAL CHARACTERISTICS[3], [4, CH. 3]



FLORES ISLAND

- Radial 15 kV distribution network
- Total demand : ~2 MW
- Diesel generator with total capacity: 2.5 MW
- Hydro power generator with total capacity: 1.3 MW (reservoir)
- Wind turbine with total capacity: 0.6 MW

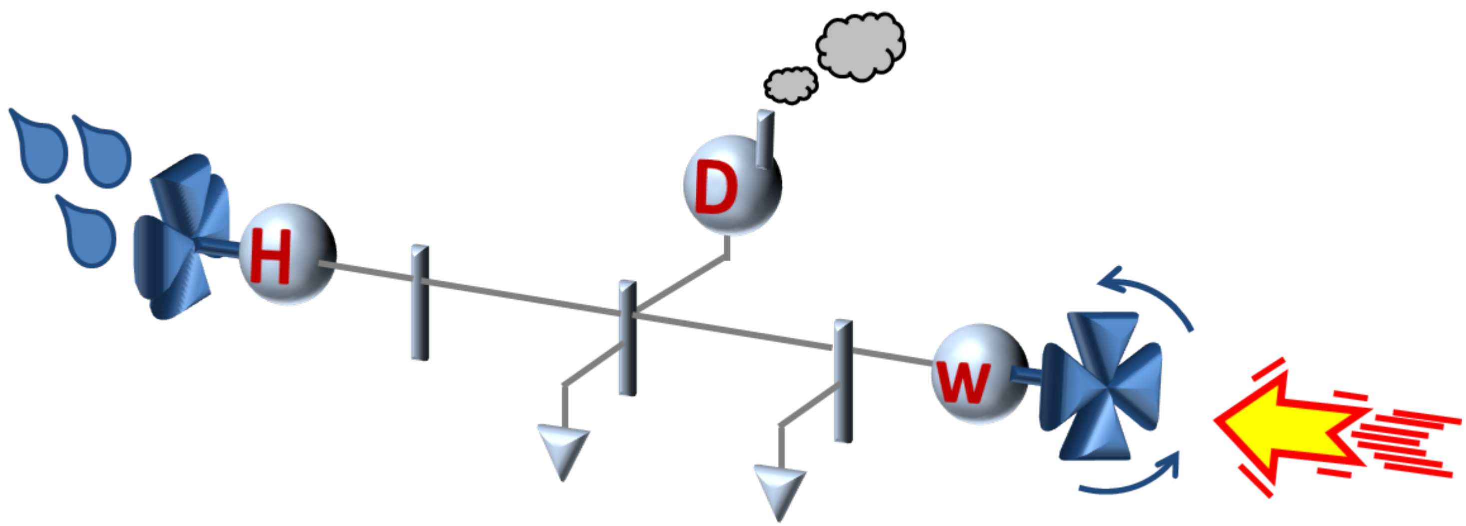


SAO MIGUEL ISLAND

- Ring 60 kV and 30 kV distribution network
- Total demand - ~70 MW
- Two large diesel generators with total capacity: 97 MW
- Two large geothermal plants with total capacity: 27 MW
- 7 small hydro power generator with total capacity: 5 MW

M. Honarvar Nazari and M. Ilić, “Electrical Networks of Azores Archipelago”, Chapter 3, Engineering IT-Enabled Electricity Services, Springer 2012.

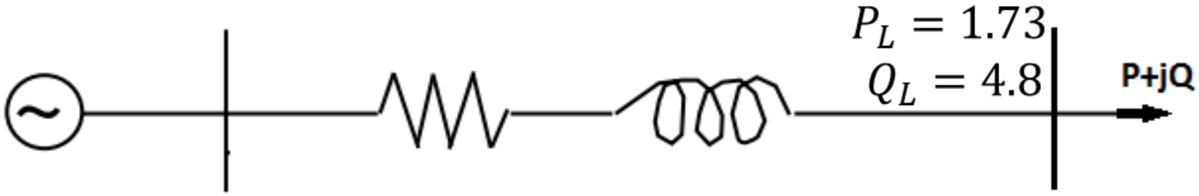
Flores Island Power System*



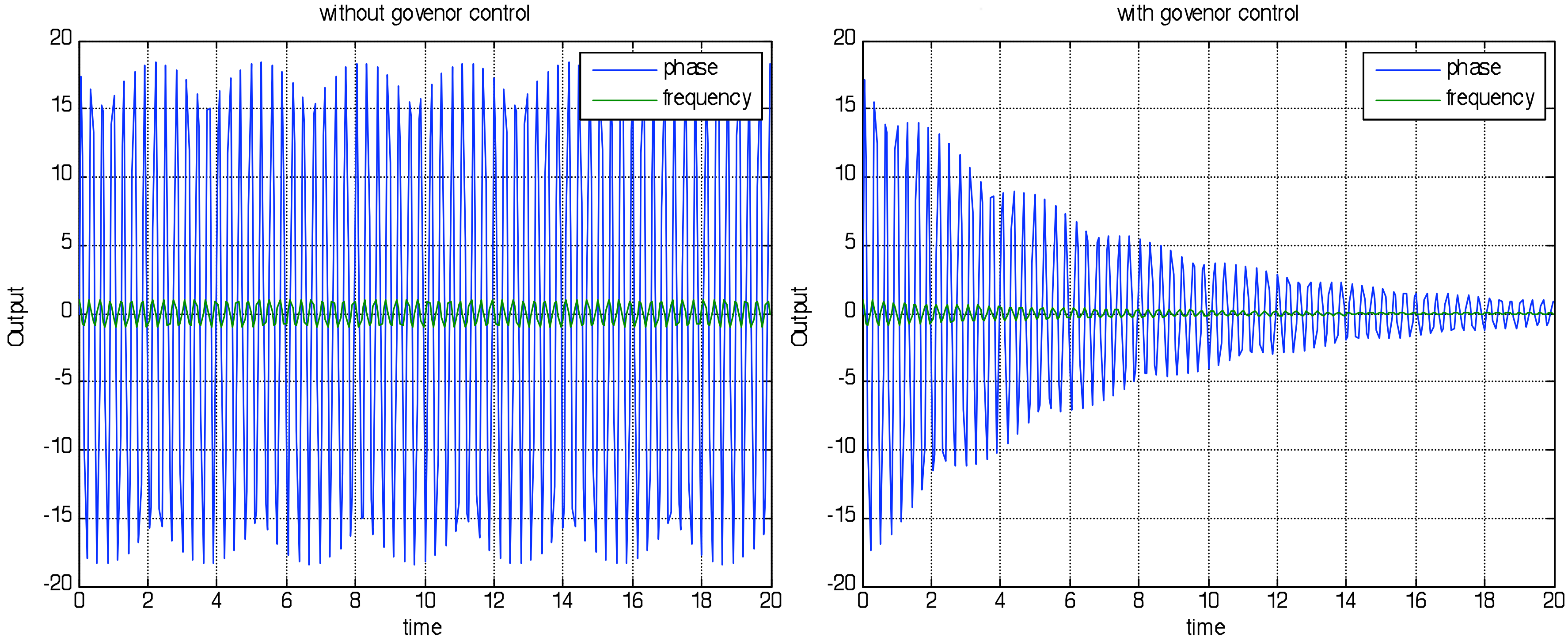
H – Hydro
D – Diesel
W – Wind

*Sketch by Milos Cvetkovic

Constant power (case 1)



Microgrid



$$V_2 = 1.07$$
$$\theta_2 = 0.1556\, rad$$

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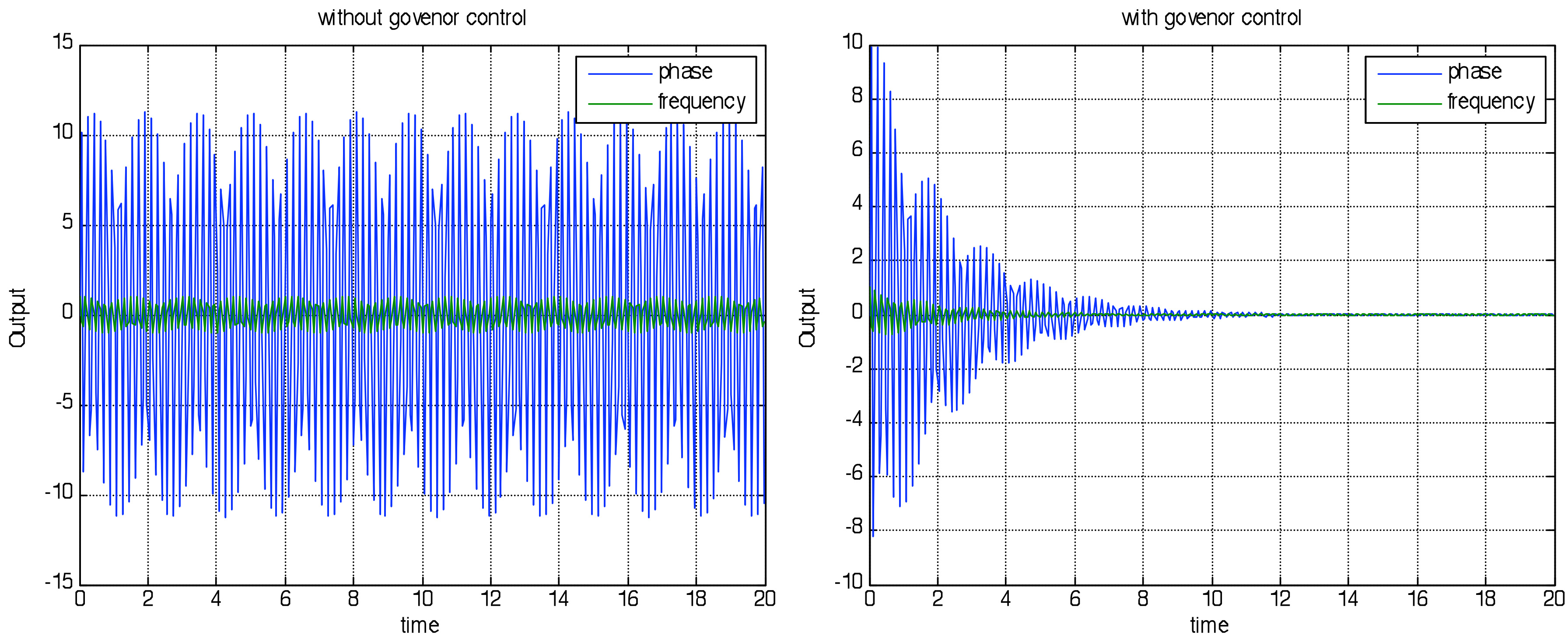
Constant power (case 2)



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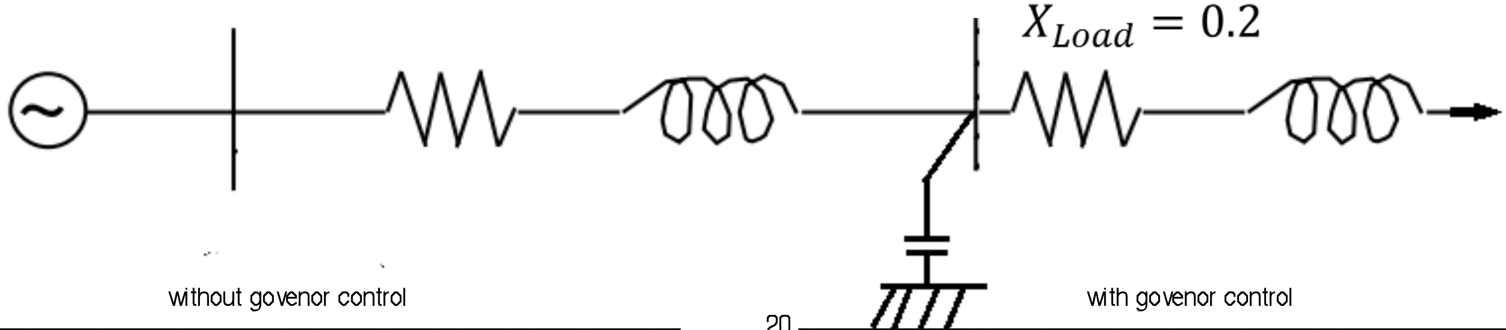
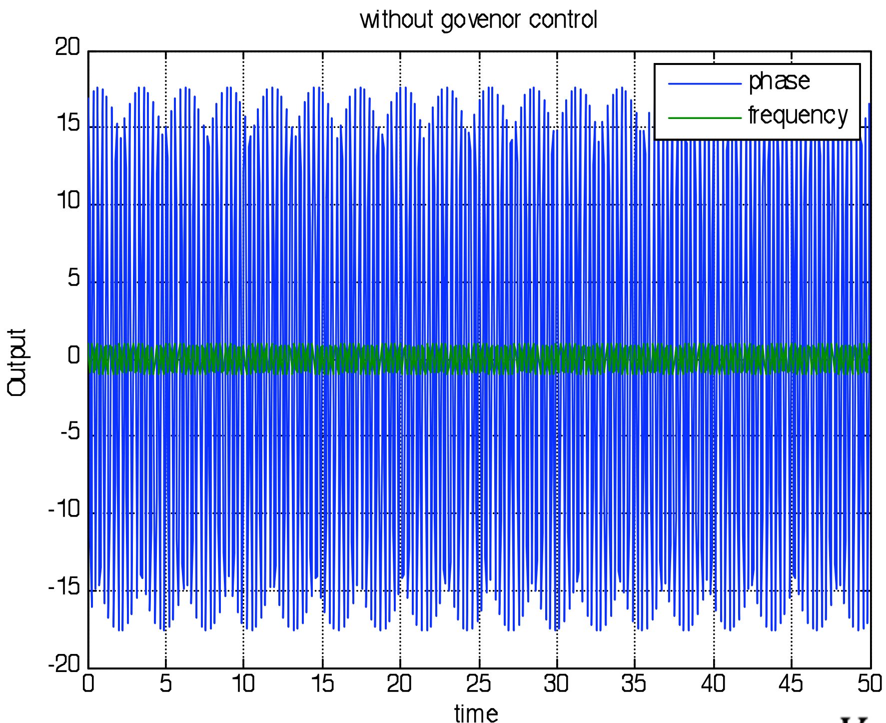
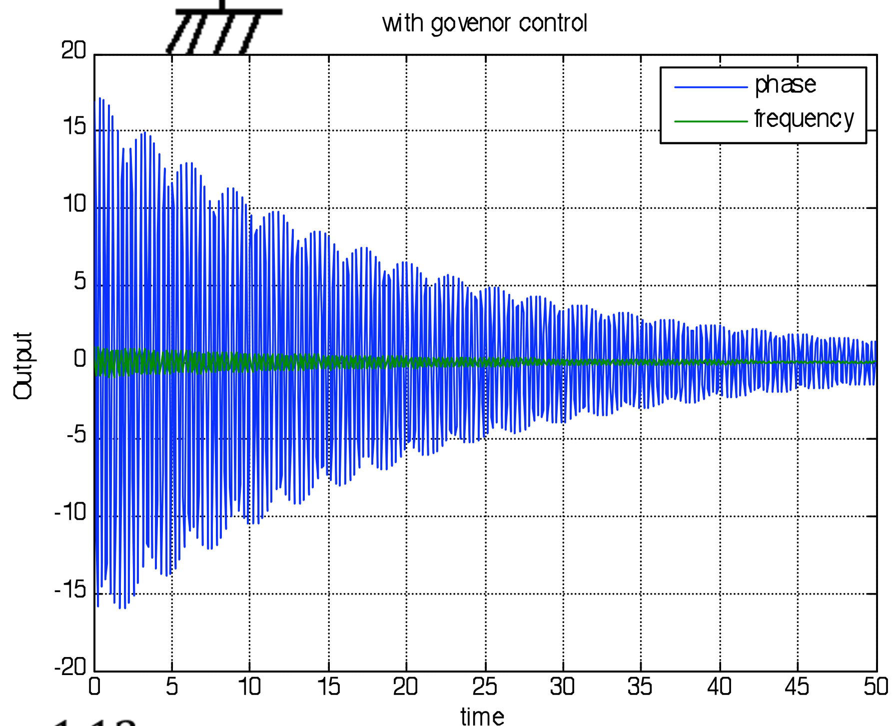




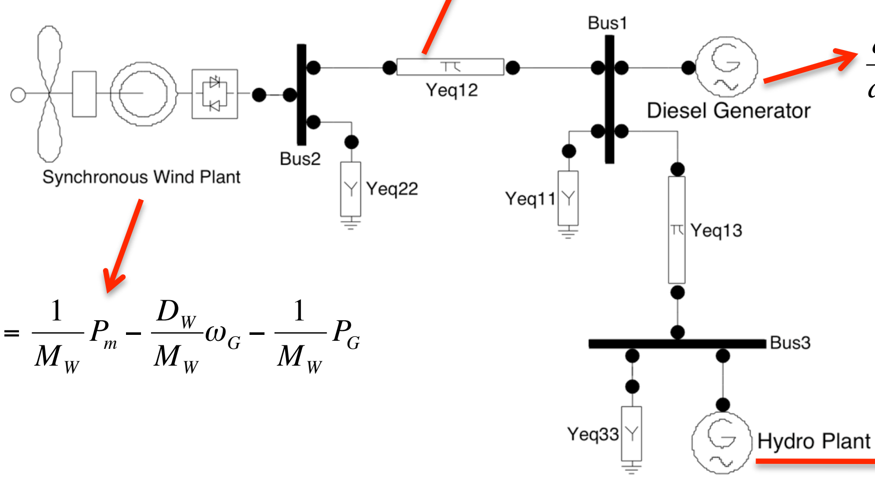


$V_2 = 1.12$
$\theta_2 = 0.256\, rad$

DYNAMIC MODEL OF FLORES ISLAND [4,CH.17]

$$\hat{K}p = \hat{J}_{GG} - \hat{J}_{GL}\hat{J}_{LL}^{-1}\hat{J}_{LG}$$

$$Yeq_{ij} = Kp_{ij}$$



One-line diagram of Flores Island

$$\frac{d}{dt}\begin{bmatrix}\omega_G\\ m_B\\ P_C\end{bmatrix} = \begin{bmatrix}\frac{-D_d}{M_d} & \frac{C_c}{M_d} & 0\\ \frac{-C_d \times K_d}{T_d \times R_c} & \frac{-1}{T_d} & \frac{-C_d \times K_d}{T_d}\\ K_I & 0 & 0\end{bmatrix}\begin{bmatrix}\omega_G\\ m_B\\ P_C\end{bmatrix} + \begin{bmatrix}\frac{-1}{M_d}\\ 0\\ 0\end{bmatrix}P_G + \begin{bmatrix}0\\ 0\\ 1\end{bmatrix}\omega_G^{ref}$$

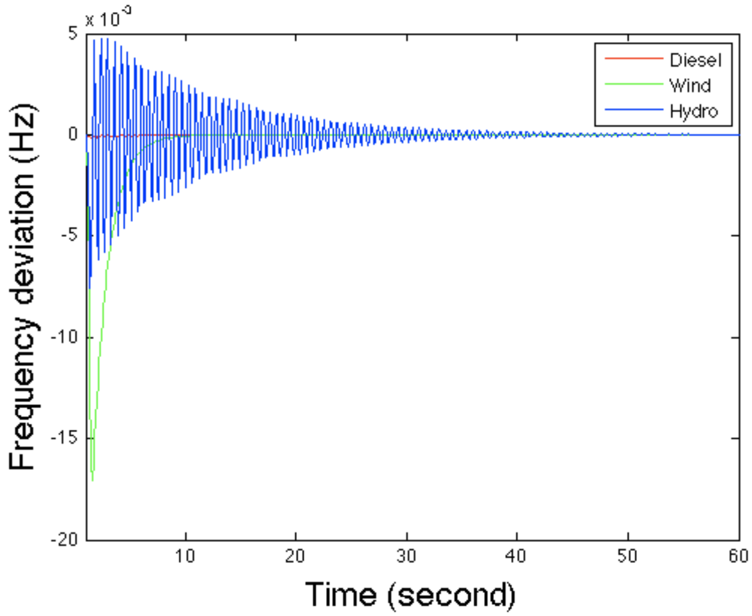
$$\frac{d\omega_G}{dt} = \frac{1}{M_W}P_m - \frac{D_W}{M_W}\omega_G - \frac{1}{M_W}P_G$$

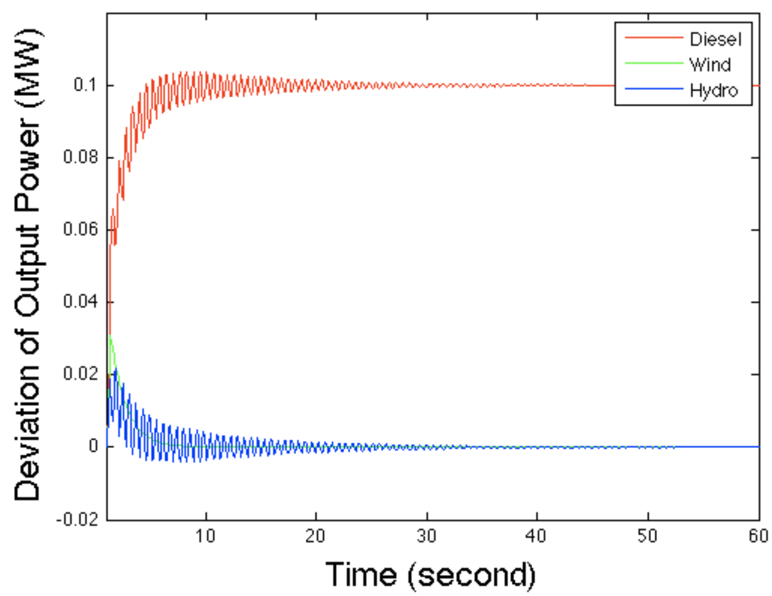
$$\frac{d}{dt}\begin{bmatrix}\omega_G\\ q\\ v\\ a\end{bmatrix} = \begin{bmatrix}\frac{-(e_H + D_H)}{M_H} & \frac{k_q}{M_H} & 0 & \frac{-k_w}{M_H}\\ \frac{1}{T_f} & \frac{-1}{T_d} & 0 & \frac{1}{T_w}\\ 0 & 0 & \frac{-1}{T_e} & \frac{a}{T_e}\\ \frac{-1}{T_s} & 0 & \frac{-1}{T_s} & \frac{-(r_H + r')}{T_s}\end{bmatrix}\begin{bmatrix}\omega_G\\ q\\ v\\ a\end{bmatrix} + \begin{bmatrix}\frac{-1}{M_d}\\ 0\\ 0\\ 0\end{bmatrix}P_G + \begin{bmatrix}0\\ 0\\ 0\\ \frac{1}{T_s}\end{bmatrix}\omega_G^{ref}$$

M. Ilić and **M. Honarvar Nazari**, "Small Signal Stability Analysis for Systems with Wind Power Plants: The Extended State Space-based Modeling", Chapter 17, Engineering IT-Enabled Electricity Services, Springer 2012.

SMALL-SIGNAL STABILITY OF FREQUENCY STABILITY IN FLORES [4,CH. 17]

- Decoupled Real Power Voltage Dynamic Model
  - Neglecting coupling between the electromechanical and electromagnetic parts of generators can lead to optimistic interpretation of dynamic stability.

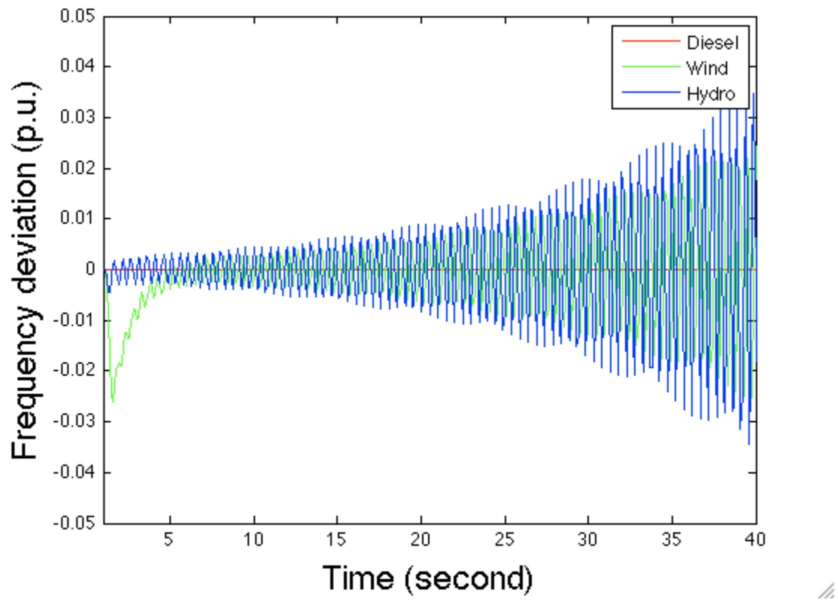


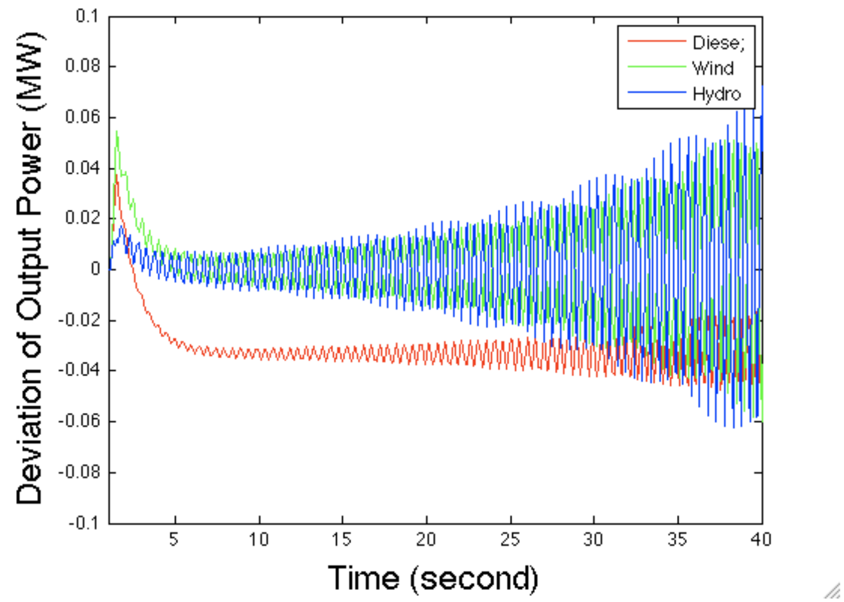


M. Honarvar Nazari and M. Ilić, “Small Signal Stability Analysis for Systems with Wind Power Plants: The Extended State Space-based Modeling”, Chapter 17, Engineering IT-Enabled Electricity Services, Springer 2012.

POSSIBLE INSTABILITY OF COUPLED VOLTAGE- FREQUENCY DYNAMICS ? [4,CH.17]

- Strong interactions between the electromagnetic and electromechanical parts of the generators could result in an overall instability in the island.





[1] M. Honarvar Nazari and M. Ilić, “Dynamic Stability of Azores Archipelago”, Chapter 14, Engineering IT-Enabled Electricity Services, Springer 2012.

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 internal sub-system level state dynamics
- Dynamics of physical interaction variables zero when the system is disconnected from other sub-systems
- A means of defining what needs coordination at the zoomed-out layer

Subsystem-level Model

❖ Standard state space model

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

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

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

Subsystem-level Model

- Interaction variable

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

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

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

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

- Dynamic model

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

- Physical interpretation
  - Driven only by **external coupling** and **internal control**
  - **Invariant** in a **closed/disconnected** and **uncontrolled system**
  - Represents the **Conservation of Power** of the **Subsystem**

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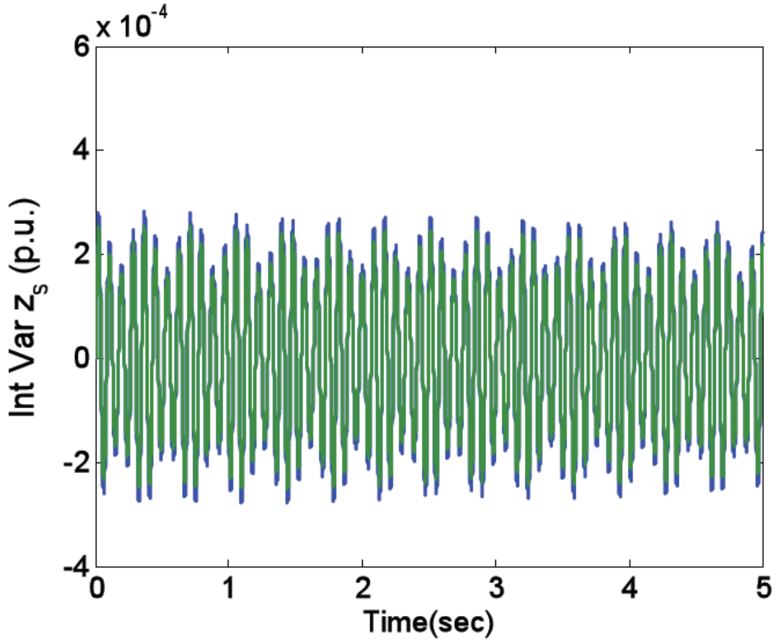
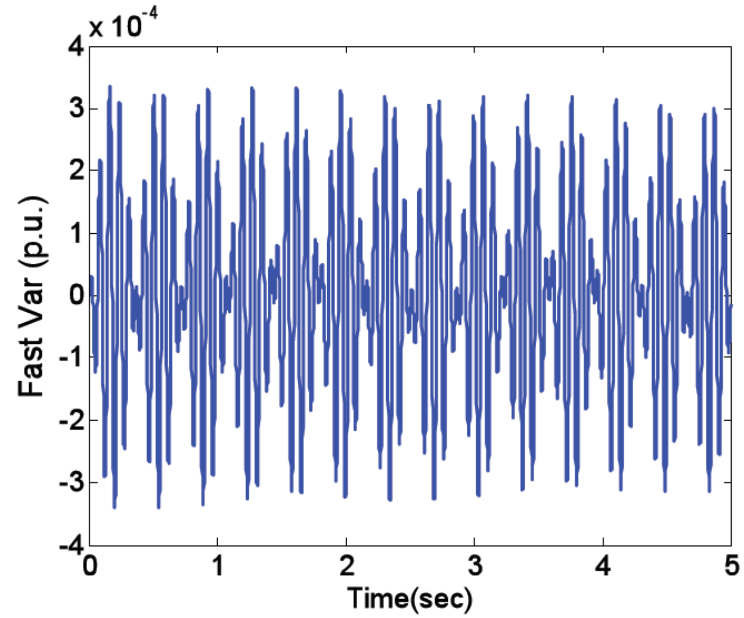
Strongly coupled subsystems

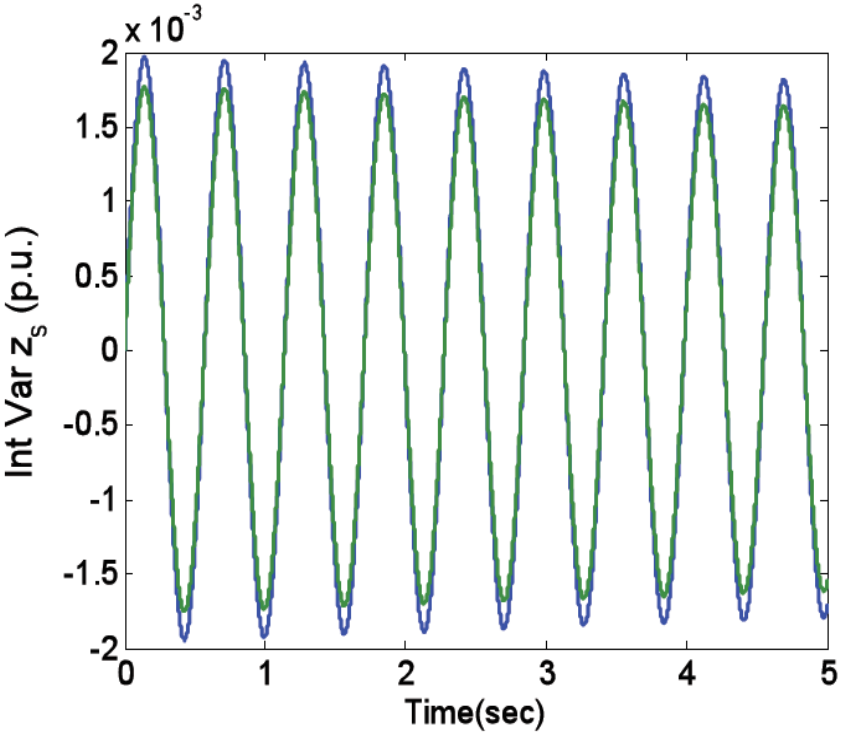
- Not possible to make the key hierarchical system assumption that fast response is always localized; dead-end to classical LSS
- Fast control must account for system-wide interactions

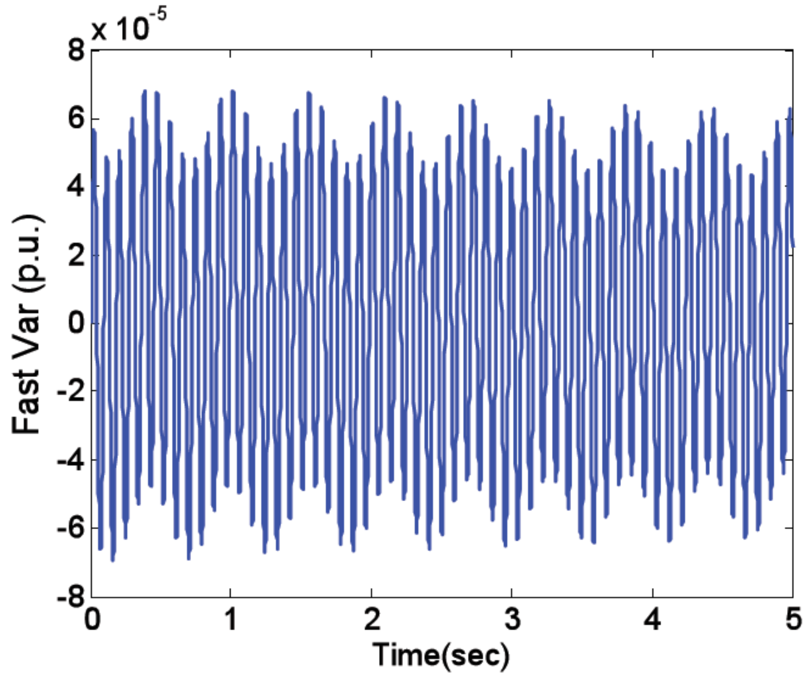




Weakly coupled subsystems

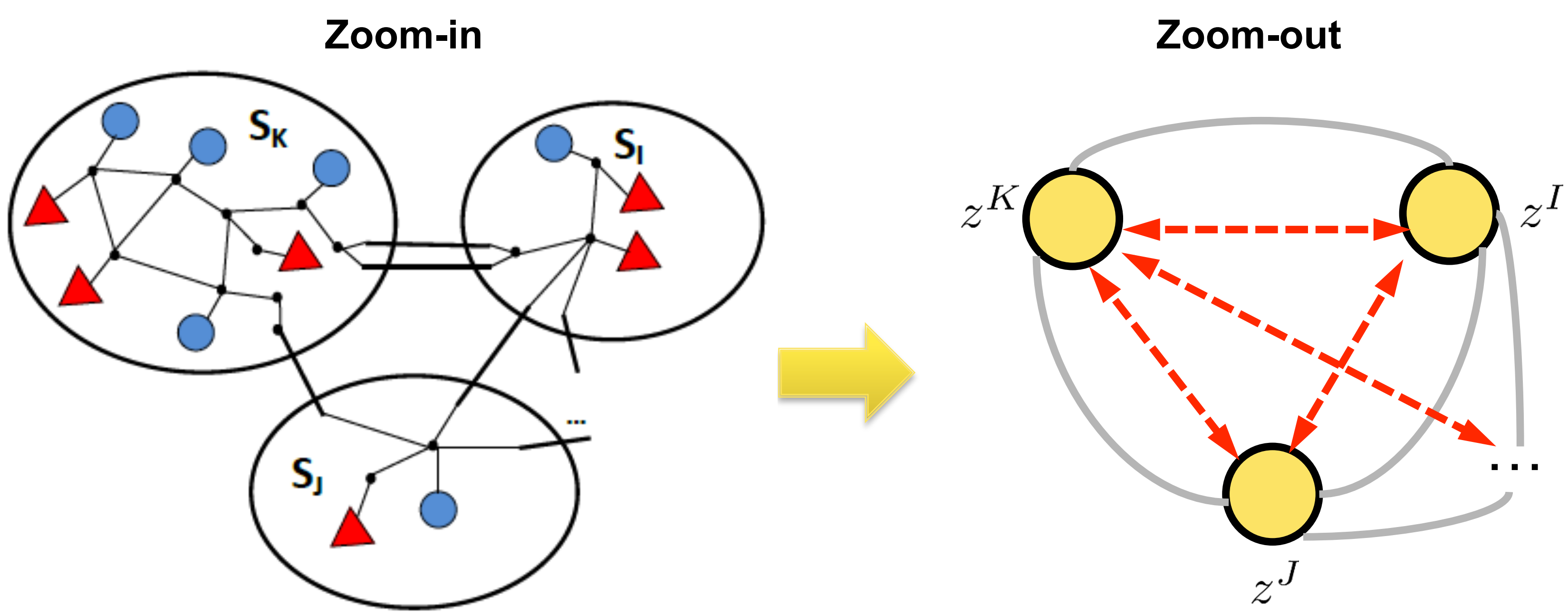
Interaction Variables of S1 and S2





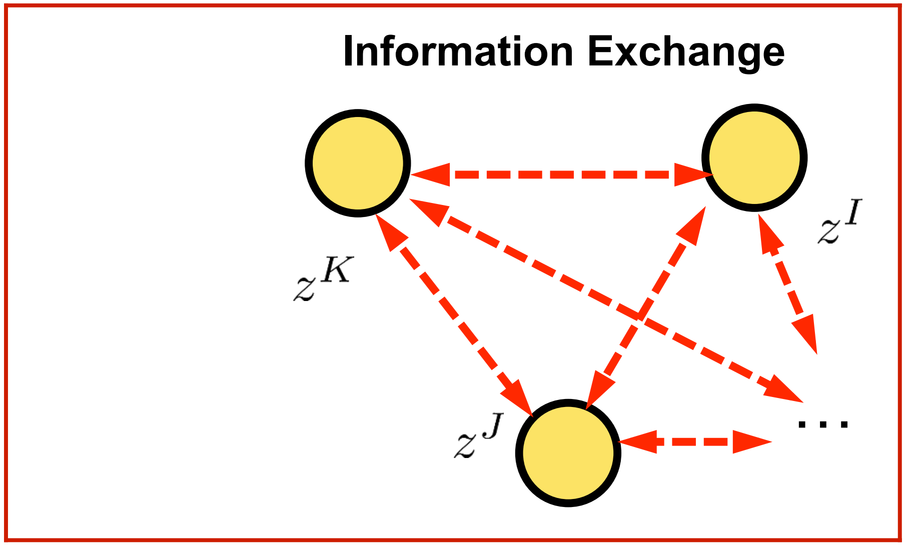
IntV-based approach to coordinated dynamics

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



IntV-based minimal coordination

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

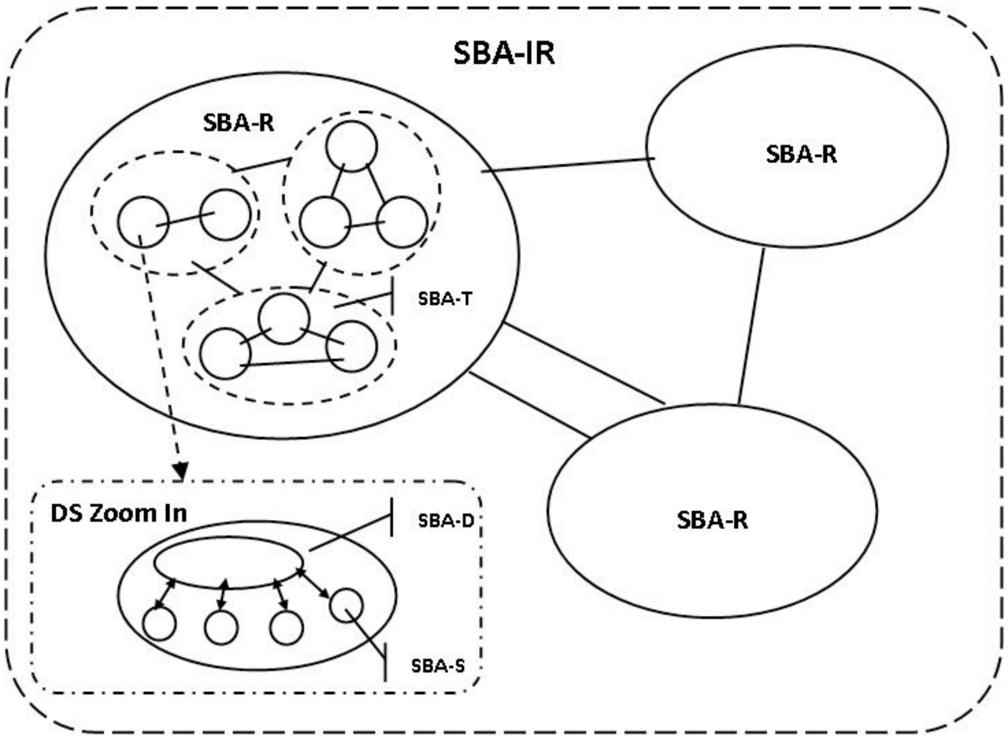


Nonlinear IntV -Cvetkovic, PhD thesis, CMU, Dec 2013

Physics/model-based spatial scaling up

- Must avoid emerging problems
- 50.2Hz problem in Germany because of poorly controlled PV
- How to aggregate the new open access systems with new technologies (wind power plants, PVs, geothermal) so that there is no closed-loop control problem?
- Must understand time-spatial interactions in the interconnected system.

Physics/Model Based Spatial Scaling Up for CPS Design



CONFLICTING OBJECTIVES—COMPLEXITY AND COST OF COMMUNICATIONS VS. COMPLEXITY AND COST OF SENSORS,CONTROL

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

-**IR**: Inter-Region

-**R**: Region

-**T**: Tertiary

-**D**: Distribution

-**S**: Smart Component

-**The actual number of layers depends on needs/ technologies available/ electrical characteristics of the grid**

``SMART BALANCING AUTHORITY” CREATED IN A BOTTOM-UP WAY (AGREGATION)--DyMonDS;
--COMPARE WITH CONVENTIONAL TOP-DOWN DECOMPOSITION

Key idea: Smart Balancing Authorities (SBAs) for Aligned Space-Time Dynamics

- Adaptive Aggregation for Aligning Temporal and Spatial Complexity
- Fast repetitive information exchange/learning within SBAs (local networks; portions of backbone system)
- Multi-layering (nested architecture) possible
- Without wide-spread nonlinear local control and carefully aggregated SBAs hard to have economic guaranteed performance
- Natural outgrowth of today's hierarchical control (Electricite de France has most advanced primary, secondary and tertiary control)

End-to-end CPS for Bulk Power Systems (Architecture 1)

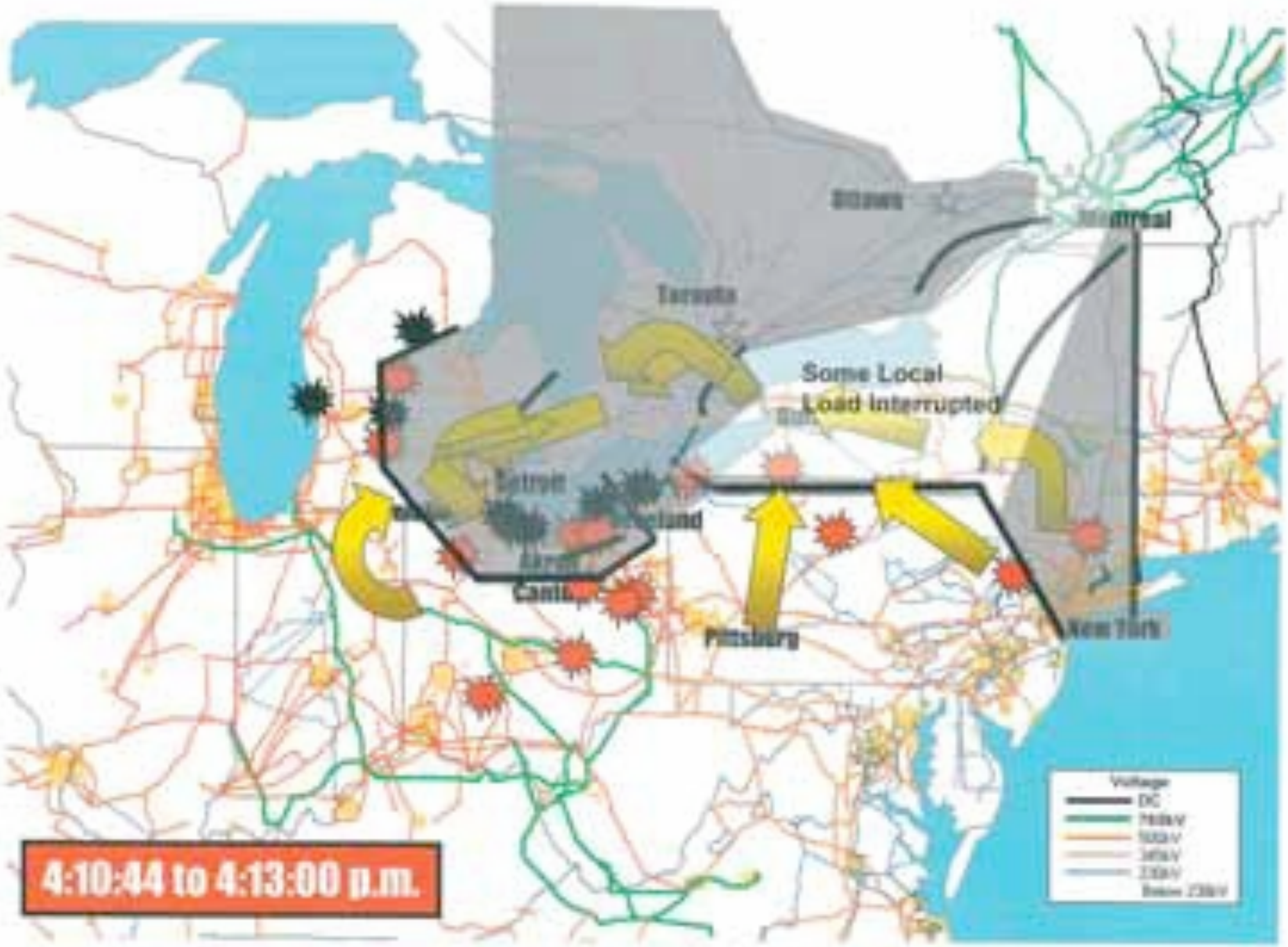
The role of big data in on-line resource management

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

On-line resource management can prevent blackouts….



Questionable practice

- **Nonlinear dynamics related**

  -Use of models which do not capture instability

  -All controllers are constant gain and decentralized (local)

  -Relatively small number of controllers

  -Poor on-line observability

- **Time-space network complexity related**

  -faster processes stable (theoretical assumption)

  -conservative resource scheduling (industry)

  -- weak interconnection

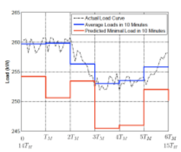
  --fastest response localized

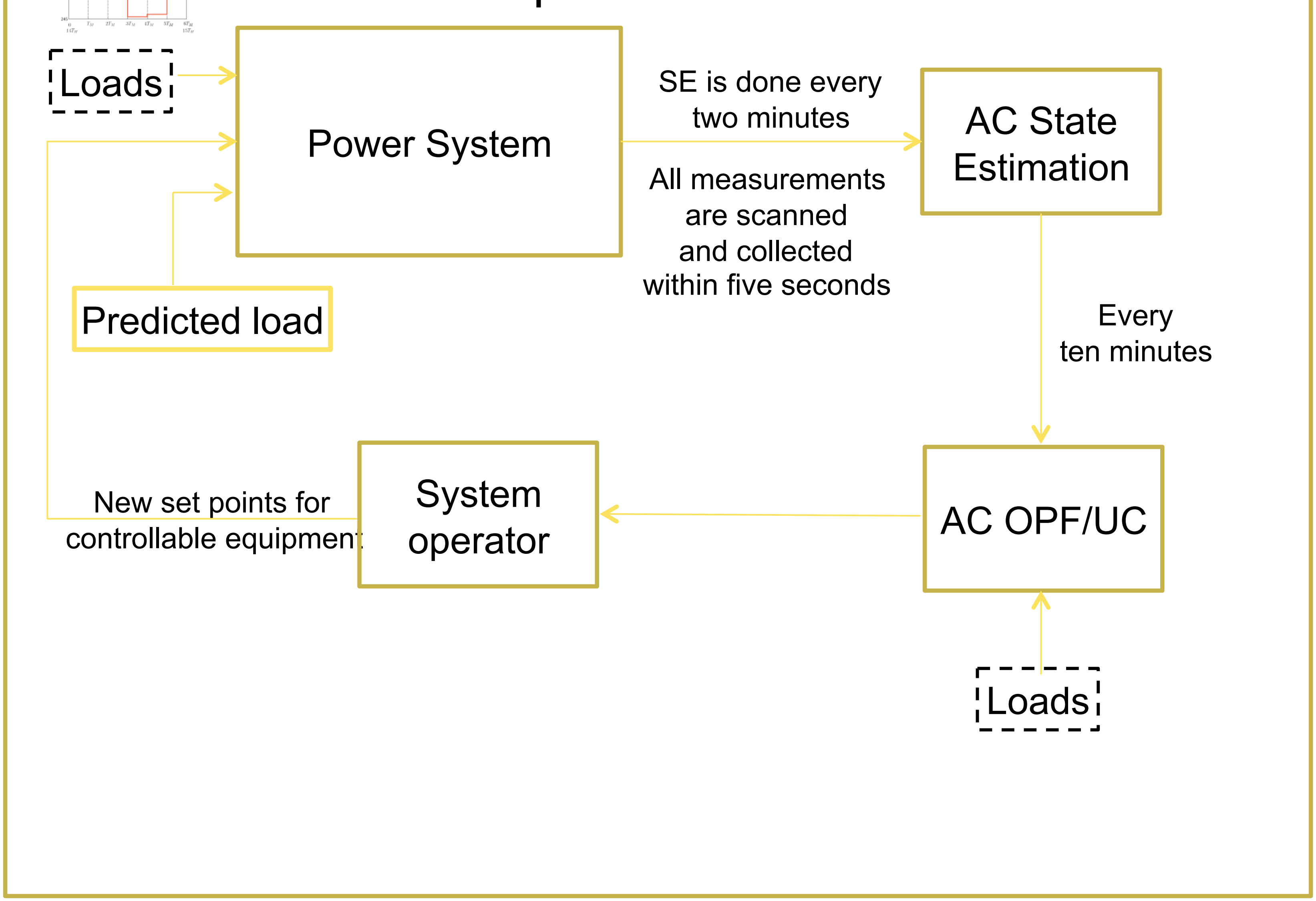
  --lack of coordinated economic scheduling

  -- linear network constraints when optimizing resource schedules

  --preventive (the ``worst case") approach to guaranteed performance in abnormal conditions

The Role of State Estimation (SE) for Optimization





The Key Role of Nonlinear LSS Network Optimization

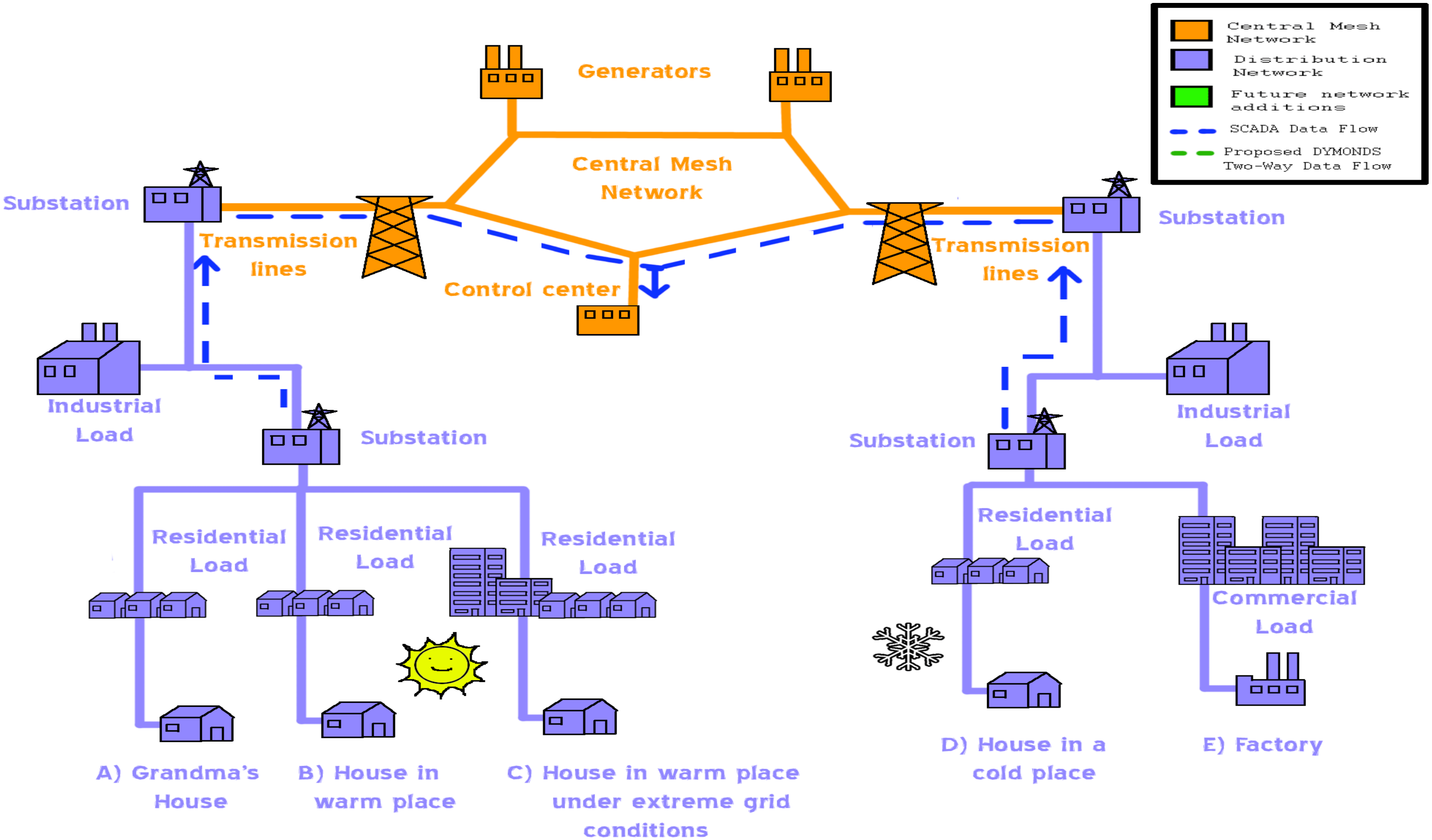
- Base case for the given NPCC system in 2002 and the 2007 projected load
- The wheel from PJM (Waldwick) through NYISO to IESO (Milton) –the maximum wheel feasible 100MW
- Optimized real power generation to support an increased wheel from PJM (Alburtis) through NYISO to IESO (Milton) –the maximum feasible wheel 1,200MW
- 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

Critical: Transform SCADA

- From single top-down coordinating management to the multi-directional multi-layered interactive IT exchange.

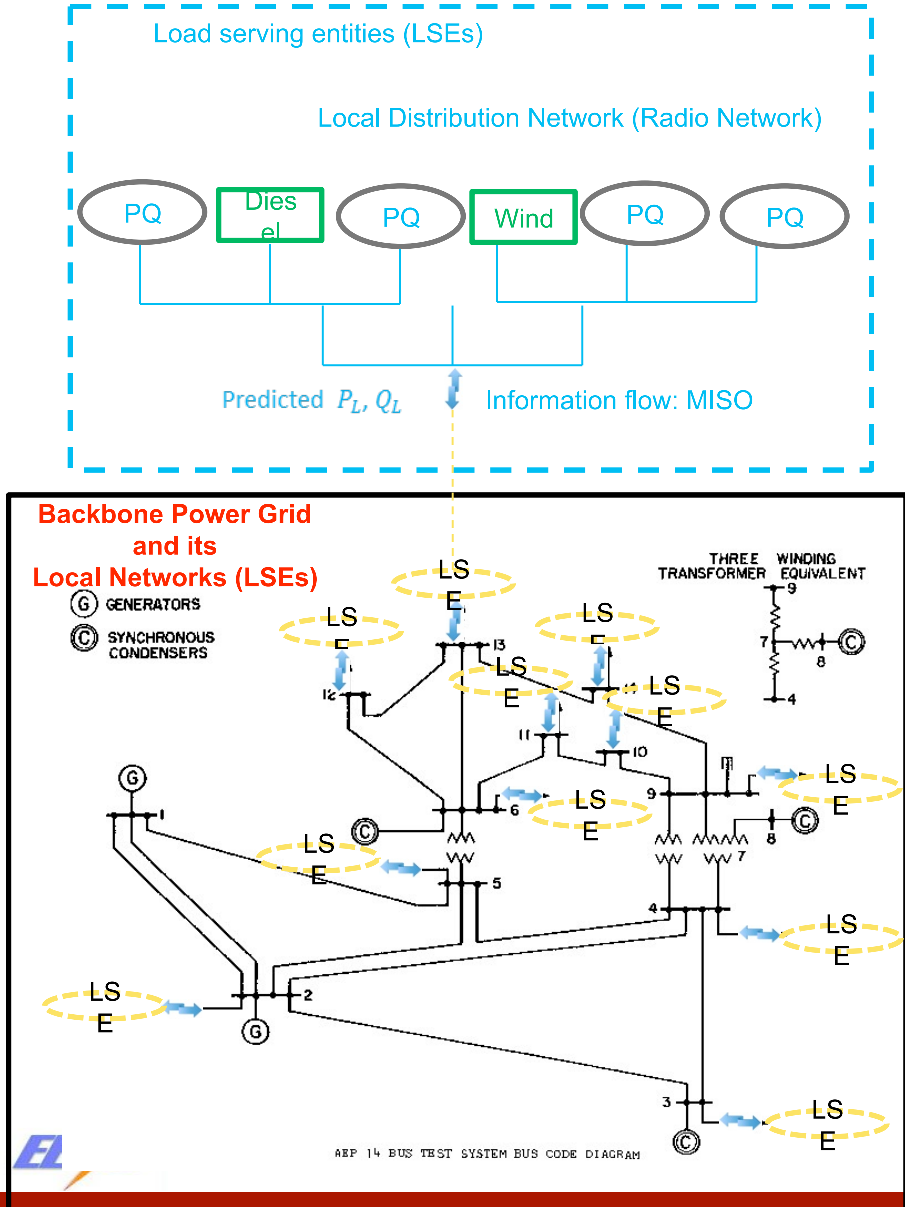
- At CMU we call such transformed SCADA Dynamic Monitoring and Decision Systems (DYMONDS) and have formed a Center to work with industry and government on: (1) new models to define what is the type and rate of key IT exchange; (2) new decision tools for self-commitment and clearing such commitments. \http:www.eesg.ece.cmu.edu.

Basic cyber system today –backbone SCADA

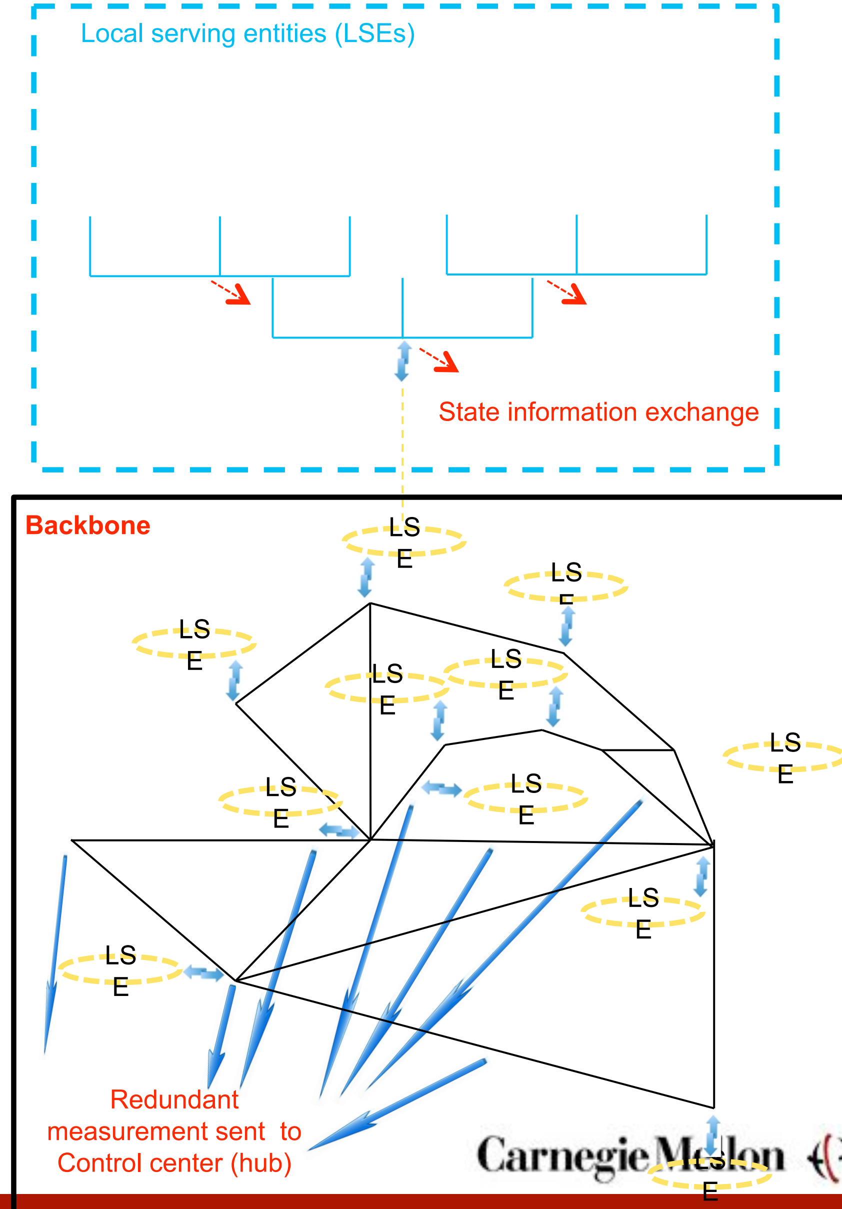


Physical and Information Network Graphs Today

Network graph of the physical system



Information graph of today's SCADA



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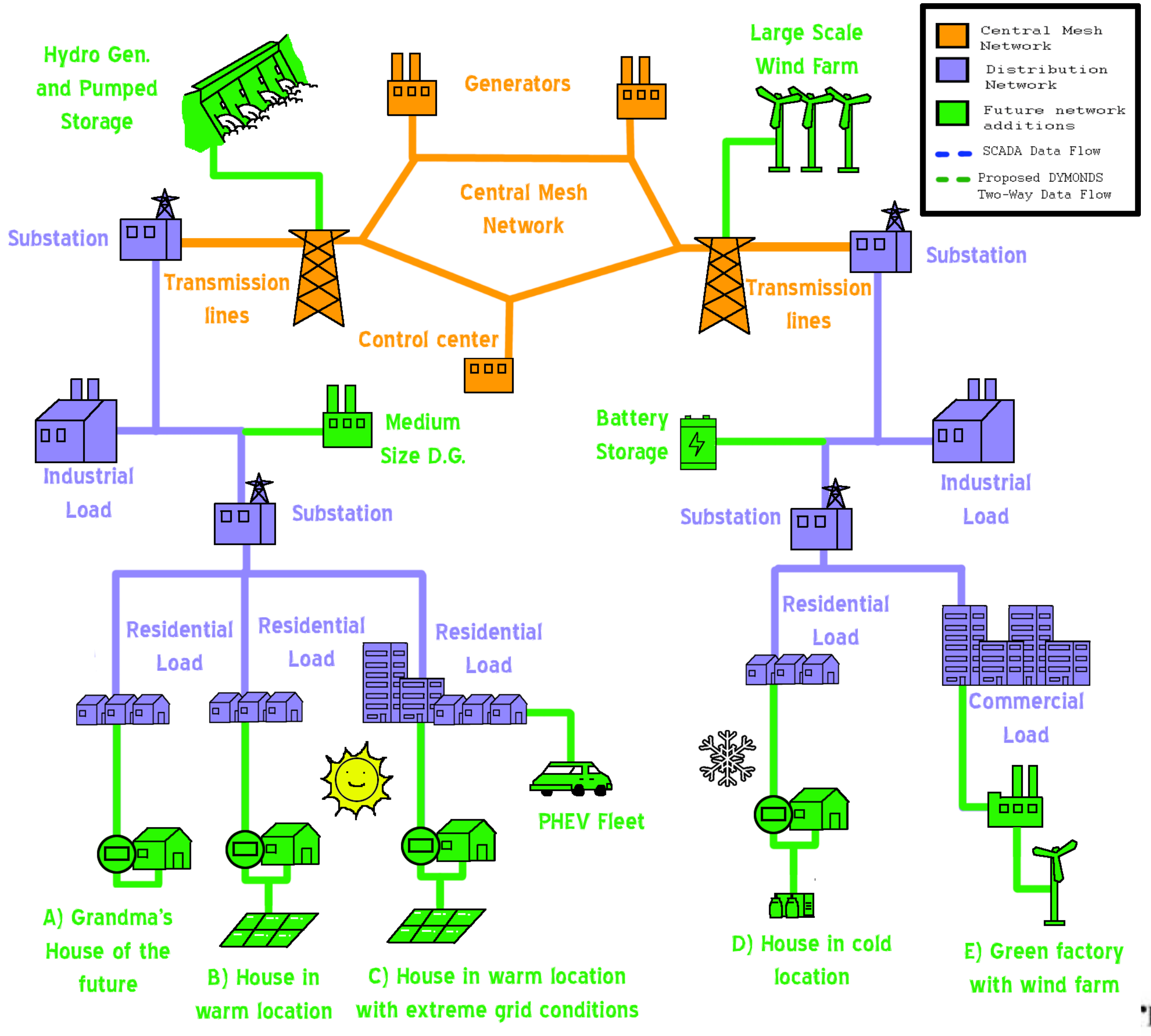
Future Smart Grid (Physical system)



DyMonDS Approach

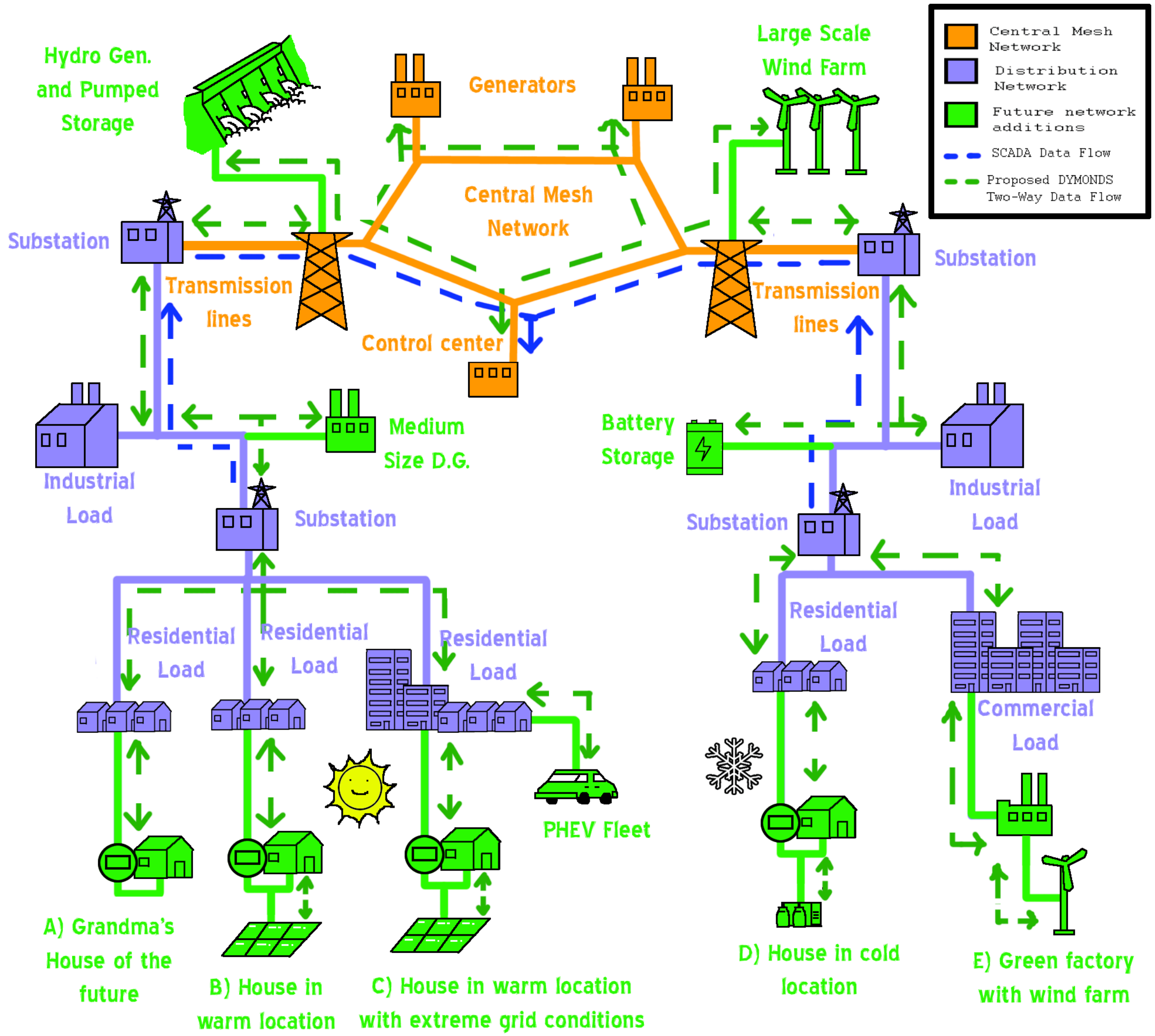
- Physics-based modeling and local nonlinear stabilizing control; new controllers (storage,demand control); new sensors (synchrophasors) to improve observability
- Interaction variables-based modeling approach to manage time-space complexity and ensure no system-wide instabilities
- Divide and conquer over space and time when optimizing

  -DyMonDS for internalizing temporal uncertainties and risks at the resource and user level; interactive information exchange to support distributed optimization

  -perform static nonlinear optimization to account for nonlinear network constraints

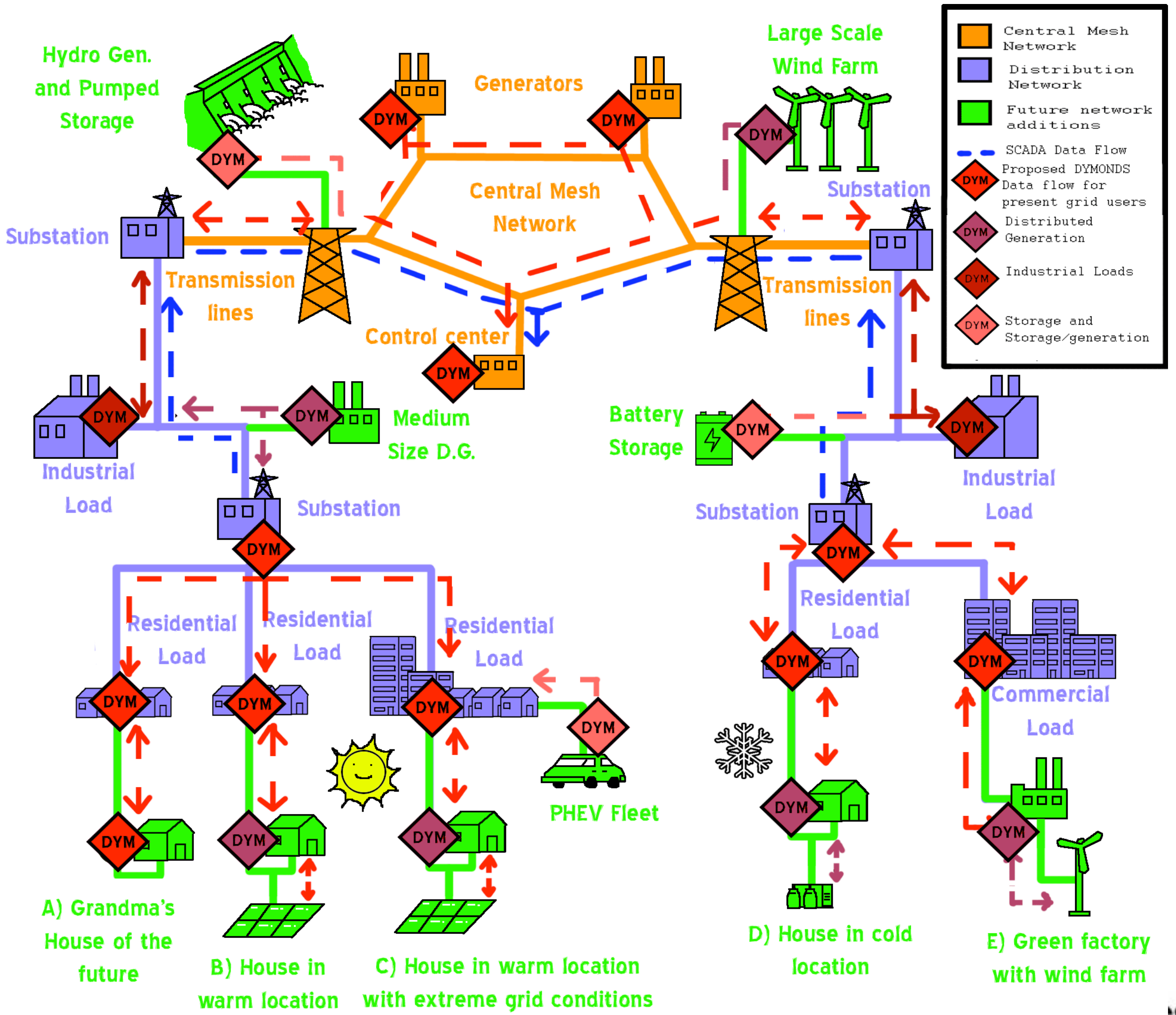
  -enables corrective actions
- Simulation-based proof of concept for low-cost green electric energy systems in the Azores Islands

New SCADA



Hydro Gen. and Pumped Storage
Generators
Large Scale Wind Farm
Central Mesh Network
Distribution Network
Future network additions
SCADA Data Flow
Proposed DYMONDS Two-Way Data Flow
Central Mesh Network
Substation
Transmission lines
Control center
Substation
Transmission lines
Battery Storage
Industrial Load
Medium Size D.G.
Substation
Industrial Load
Substation
Residential Load
Residential Load
Residential Load
Residential Load
Commercial Load
PHEV Fleet
A) Grandma's House of the future
B) House in warm location
C) House in warm location with extreme grid conditions
D) House in cold location
E) Green factory with wind farm

DYMONDS-enabled Physical Grid



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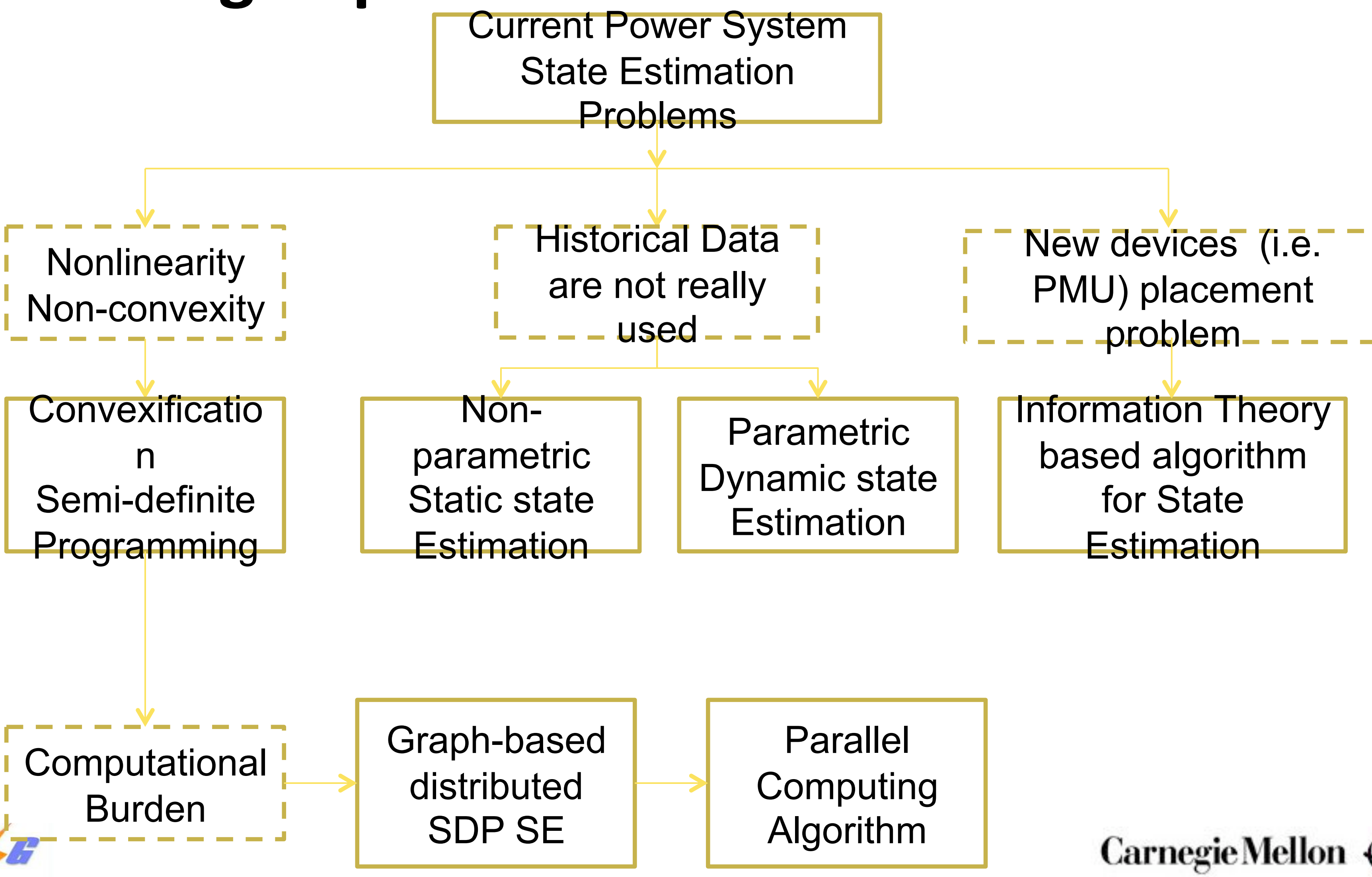
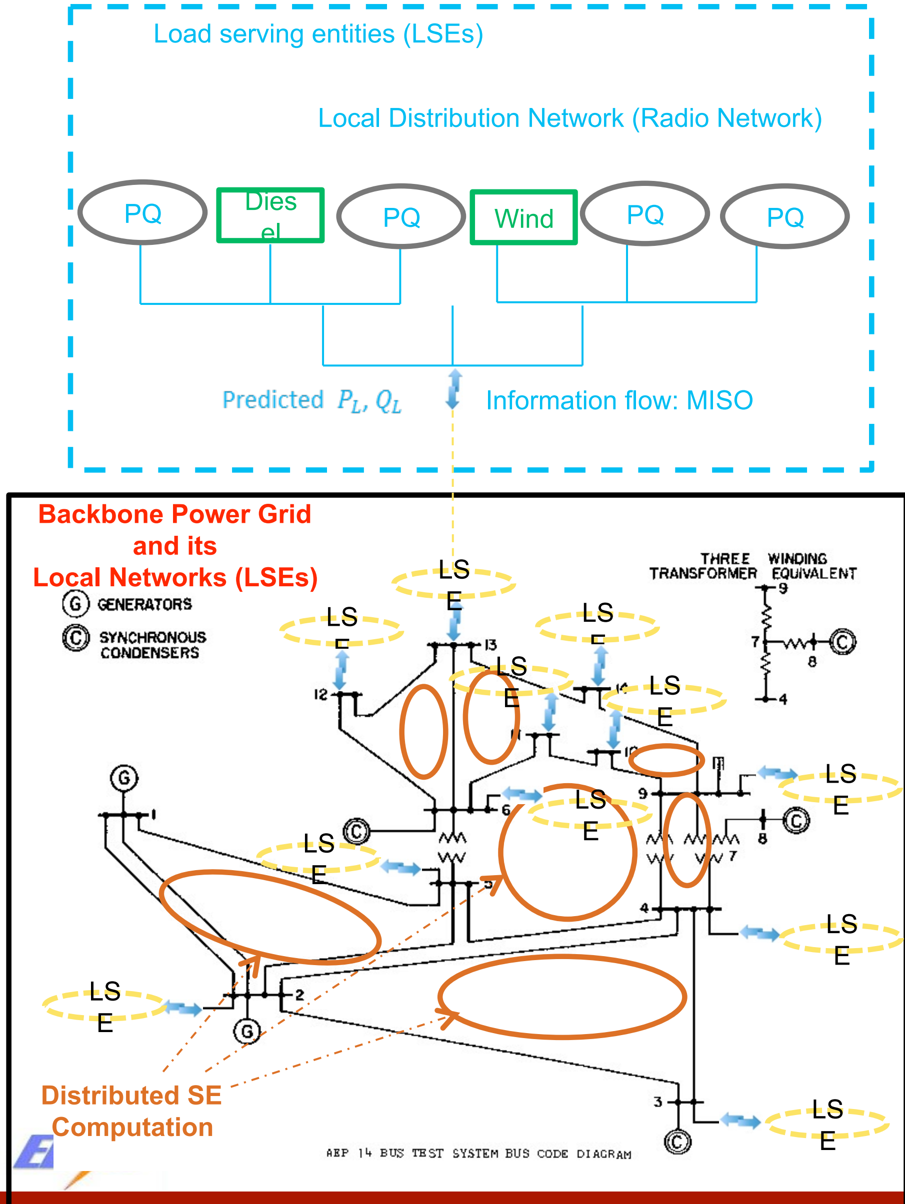
The persistent challenge: SE to support on-line scheduling implementation

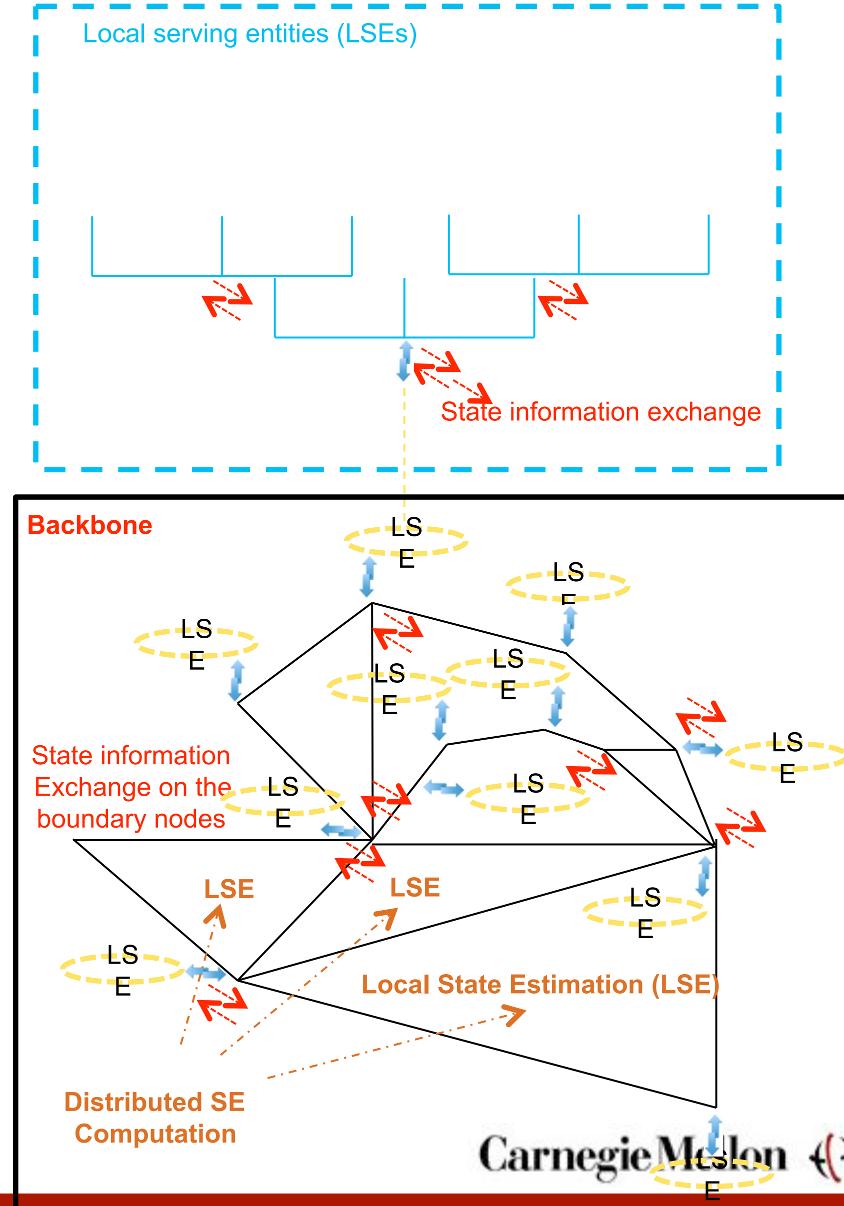


Multilayer Information for State Estimation

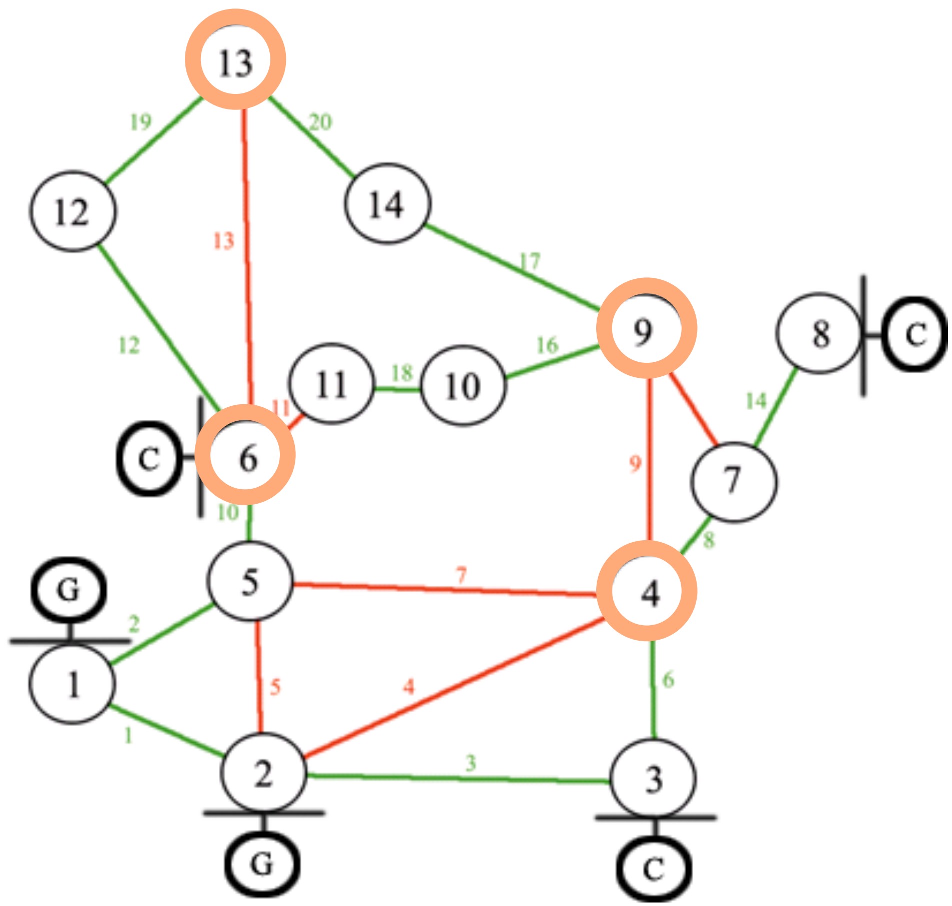
Physical Layer Online Diagram



Information Layer Diagram



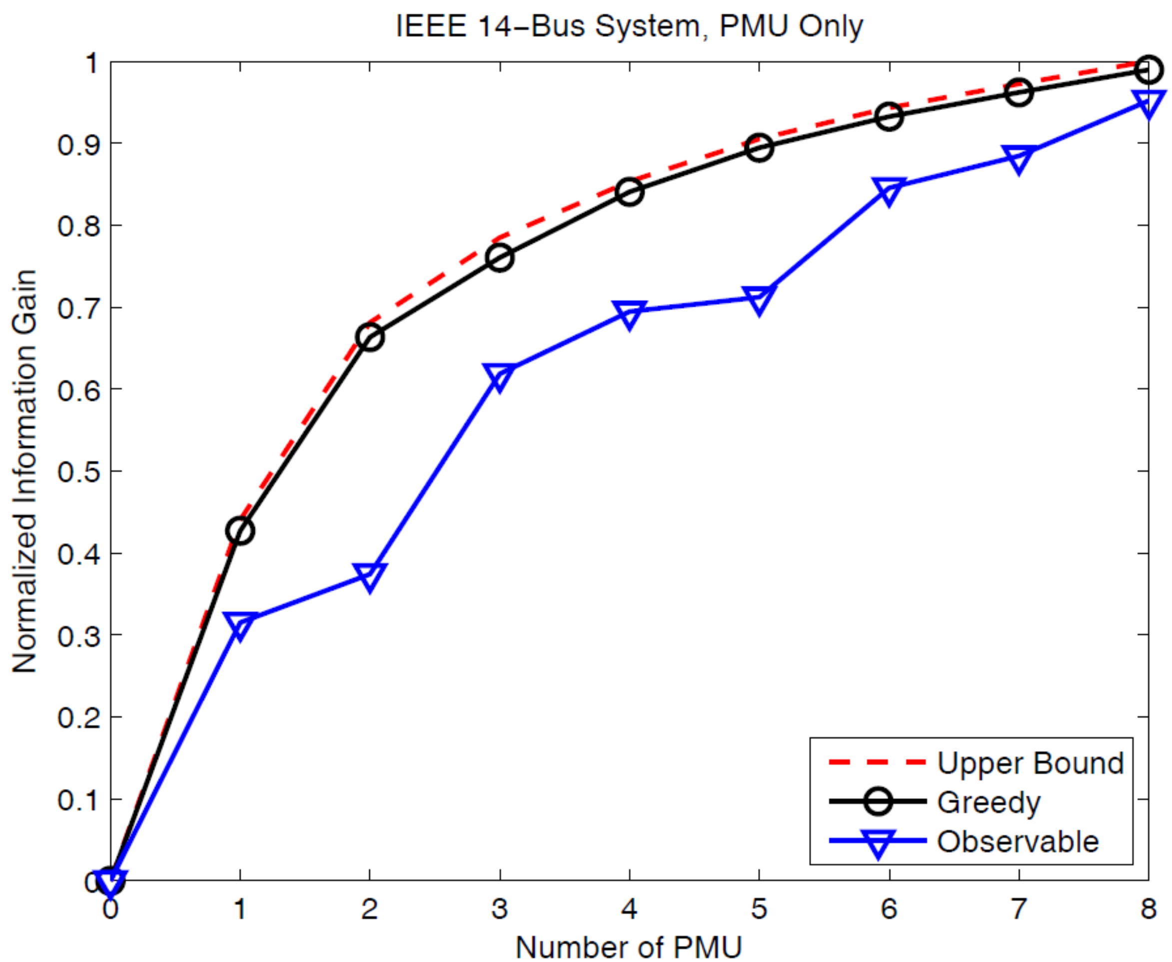
Ideal Placement of PMUs



14 bus example graphical representation

Qiao Li, Tao Cui, Yang Weng, Rohit Negi, Franz Franchetti and Marija D. Ilic, "An information theoretic approach to PMU placement in electric power systems," IEEE Transactions on Smart Grid, Special Issue on Computational Intelligence Applications in Smart Grids. (Accepted, to appear) 2013

PMU Information Gain Index



Qiao Li, Tao Cui, Yang Weng, Rohit Negi, Franz Franchetti and Marija D. Ilic, "An information theoretic approach to PMU placement in electric power systems," IEEE Transactions on Smart Grid, Special Issue on Computational Intelligence Applications in Smart Grids. (Accepted, to appear) 2013

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)

The role of cyber in bulk power grids

- On-line scheduling and automated regulation

- Potential use of big data for scheduling
  -The role of big data for accurate state estimation
  -The role of big data for on-line resource management

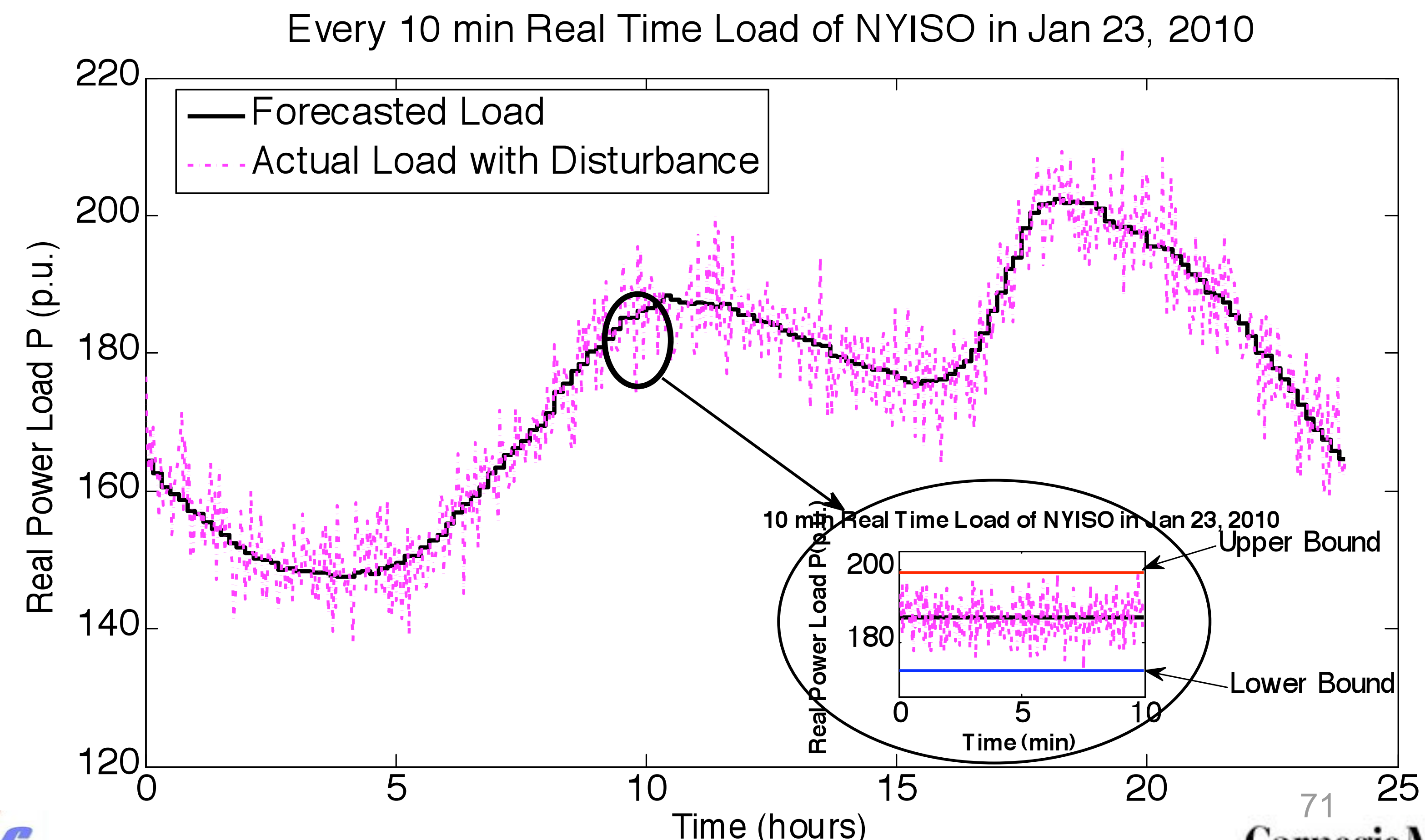
- Effects of paradigm shift on data needs

- Putting PMUs to use for enhanced Automatic Generation Control (E-AGC), enhanced Automatic Voltage Control (E-AVC) and enhanced automatic flow control (E-AFC) in systems with highly variable resources

- Possible ways forward

On-line scheduling and automatic regulation

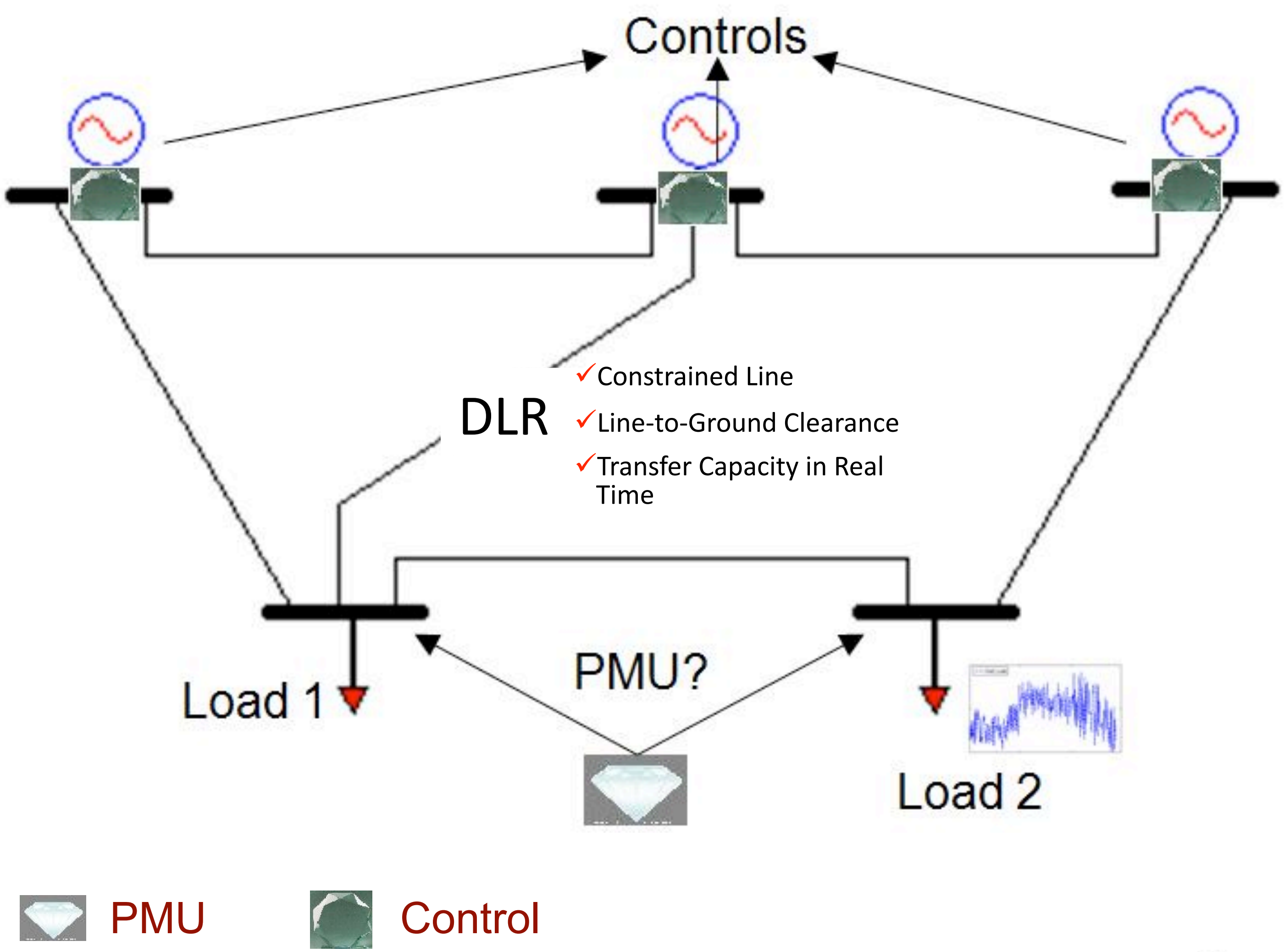
❖ System Load Curve



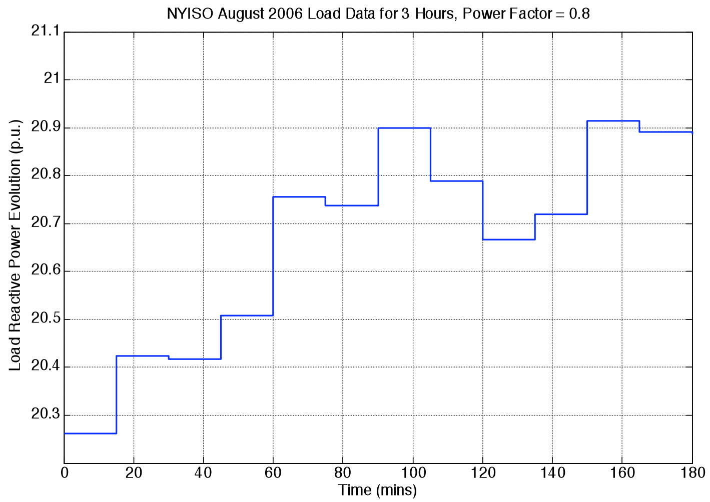
PMUs-enabled grid for efficient and reliable scheduling to balance predictable load

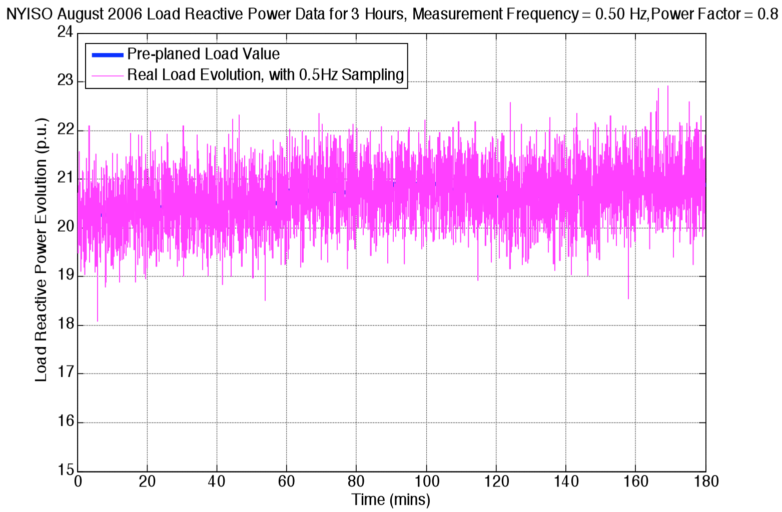
- PMUs and SCADA help more accurate state estimate of line flows, voltages and real/reactive power demand
- AC OPF utilizes accurate system inputs and computes settings for controllable grid, generation and demand equipment to help manage the system reliably and efficiently
- Adjustments done every 15 minutes
- Model-predictive generation and demand dispatch to manage ramp rates

On-line automated regulation



Predictable load and the disturbance



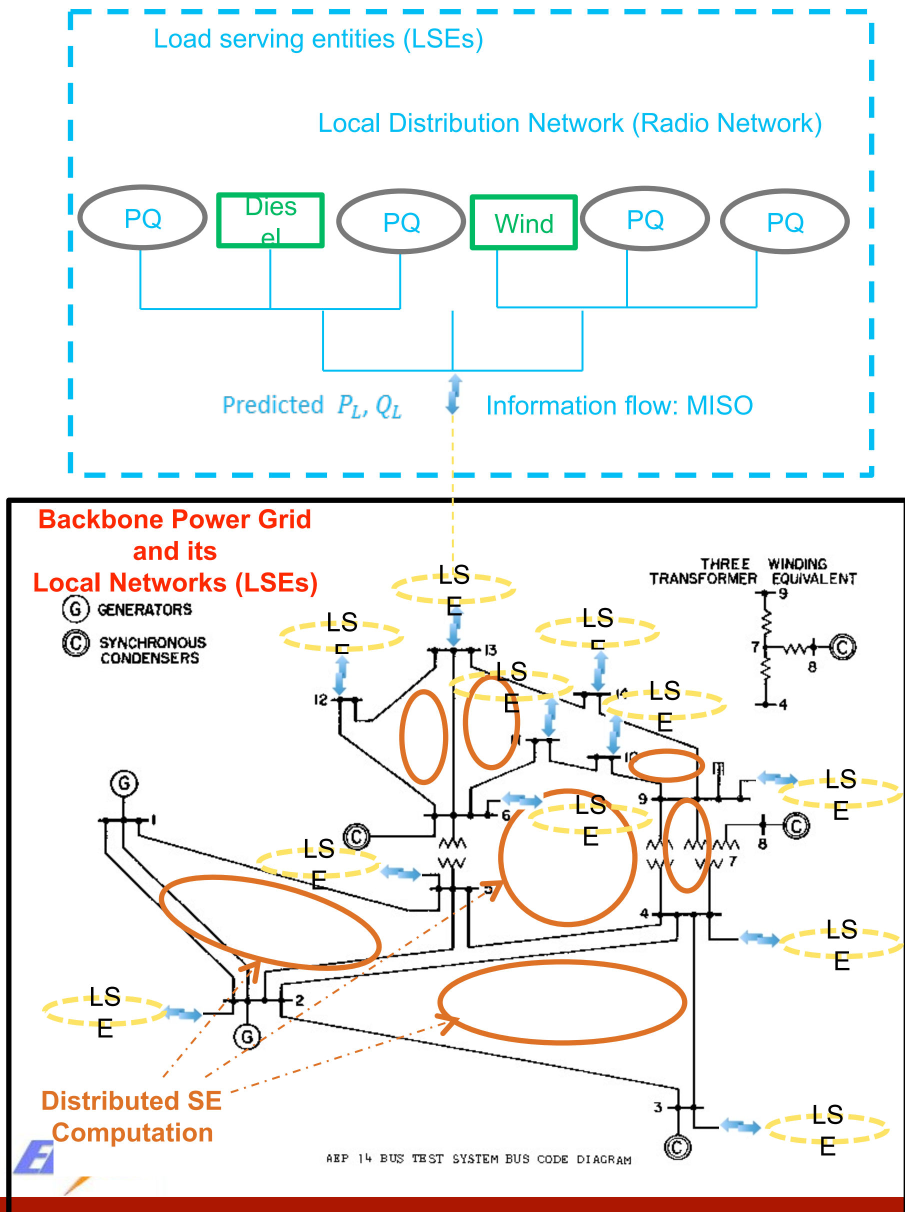


Potential use of big data for scheduling

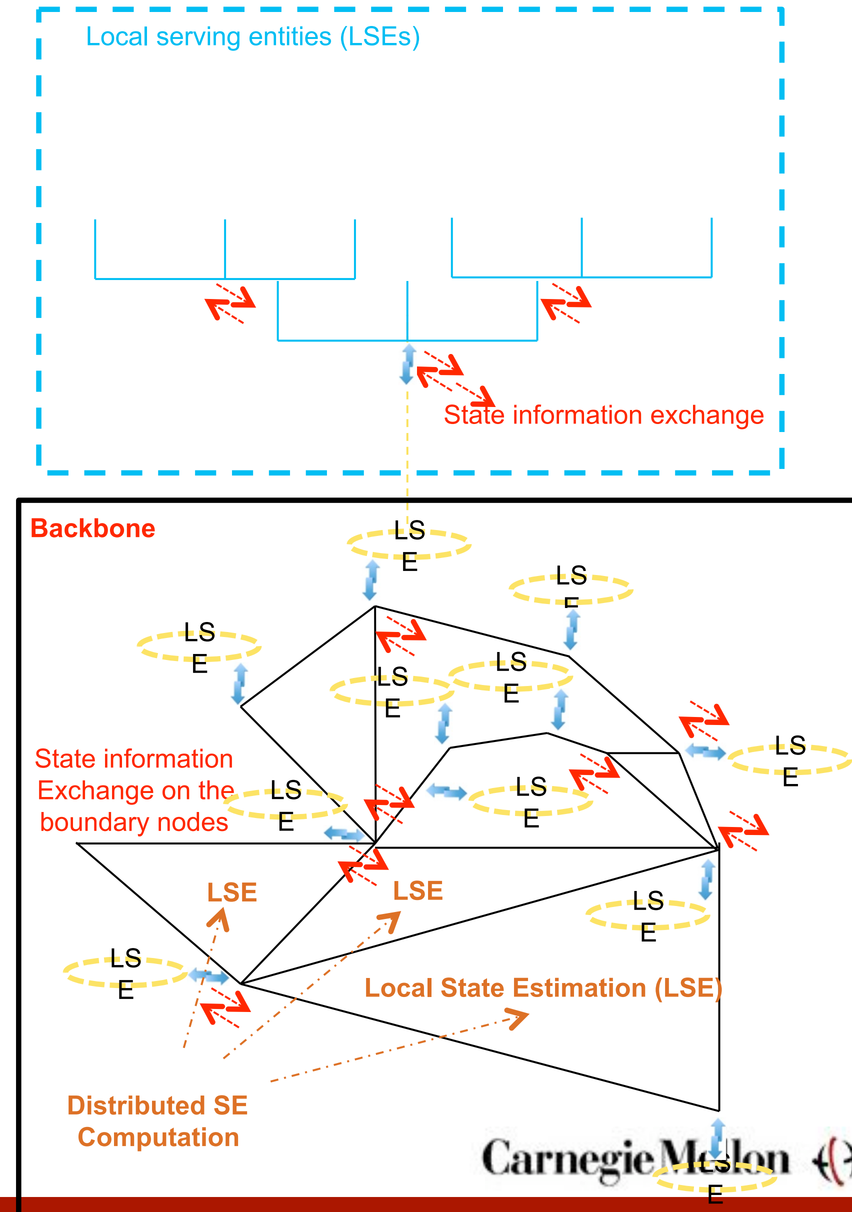
- Better time-stamped archives of large network data (inputs, states, outputs; equipment status)
- Enhanced system-level state estimation (not just static WLS)
- Begin to create data structures that reveal temporal and/or spatial correlations in complex grids; more efficient and reliable on-line resource management
- Off-line analysis (effects of large number of possible equipment failures and input variability)

Multilayer Information for State Estimation

Physical Layer Online Diagram

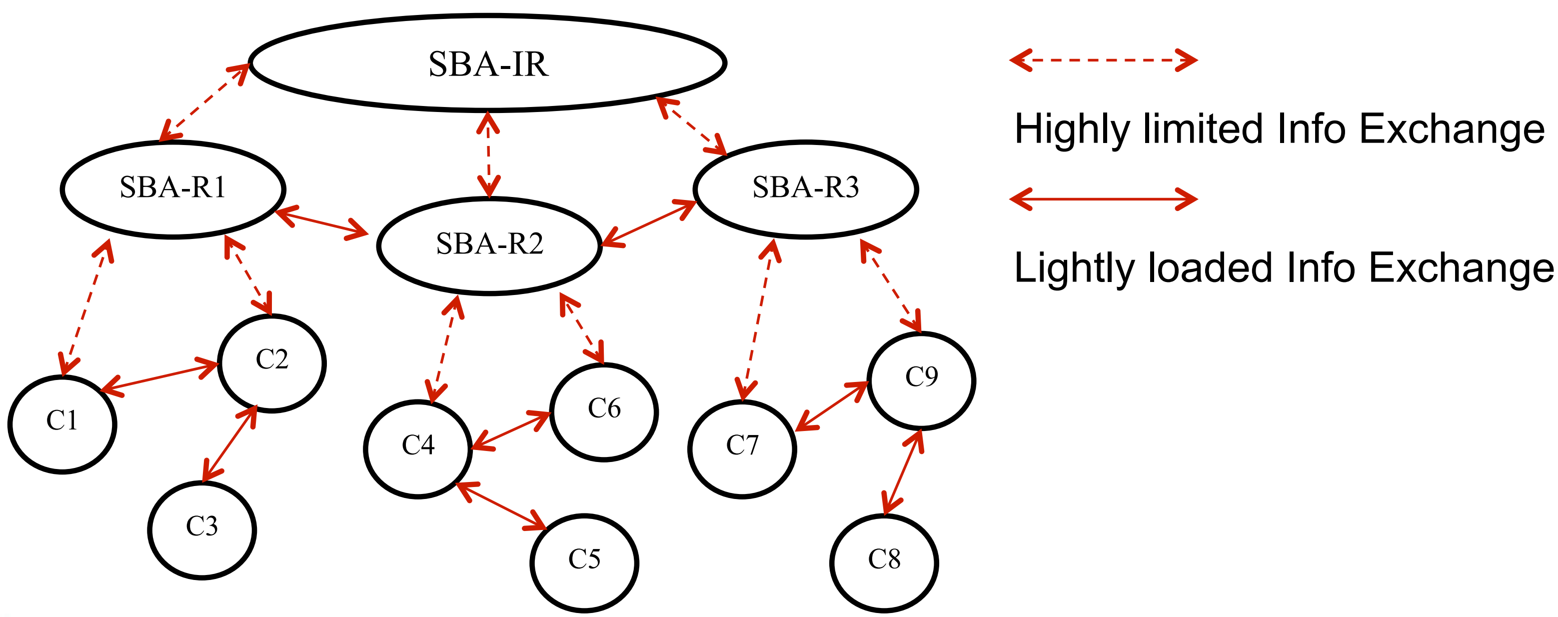


Information Layer Diagram



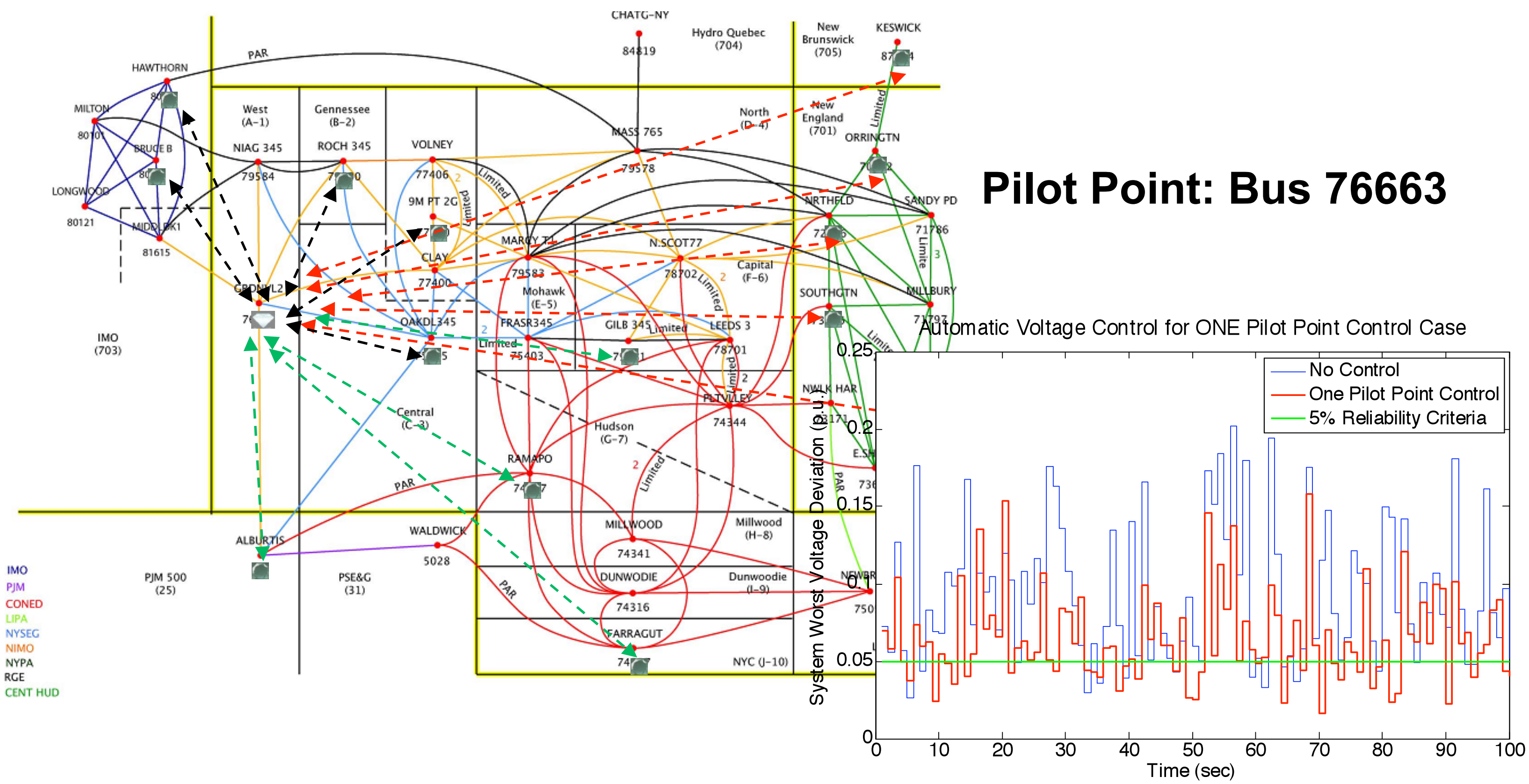
Putting PMUs to Use for E-AVC, E-AFC and E-AGC

- Need for advanced sensing technology
  - **PMUs** to measure the coupling states (voltage phase angles) on real-time
- Need for communication channels
  - Upload info to the upper layer
  - Exchange info with neighboring layers for feedback control of the coupling

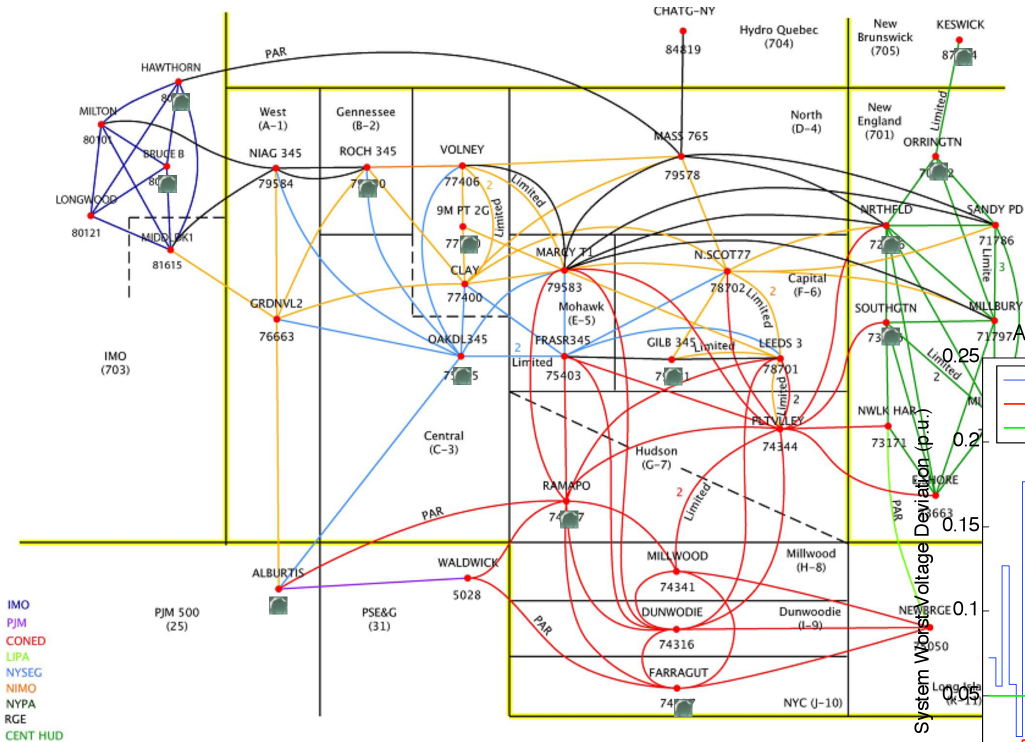


Putting PMUs to Use for AVC

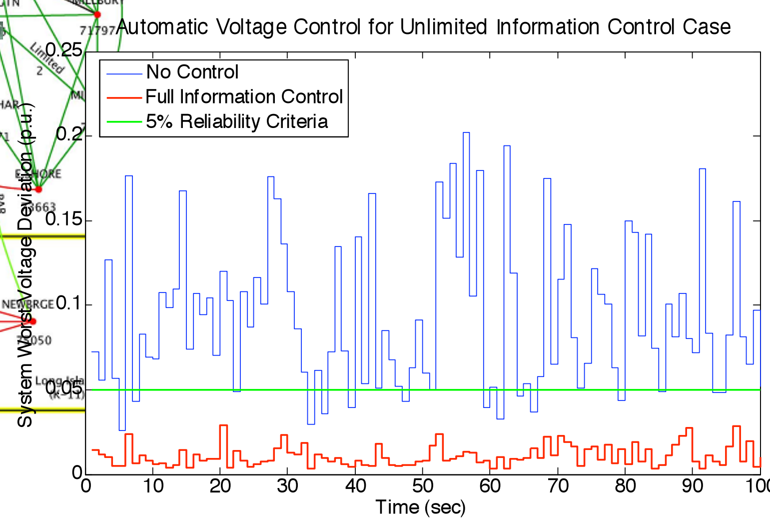
Pilot Point: Bus 76663



❖ Robust AVC Illustration in NPCC System



All load buses are Monitored



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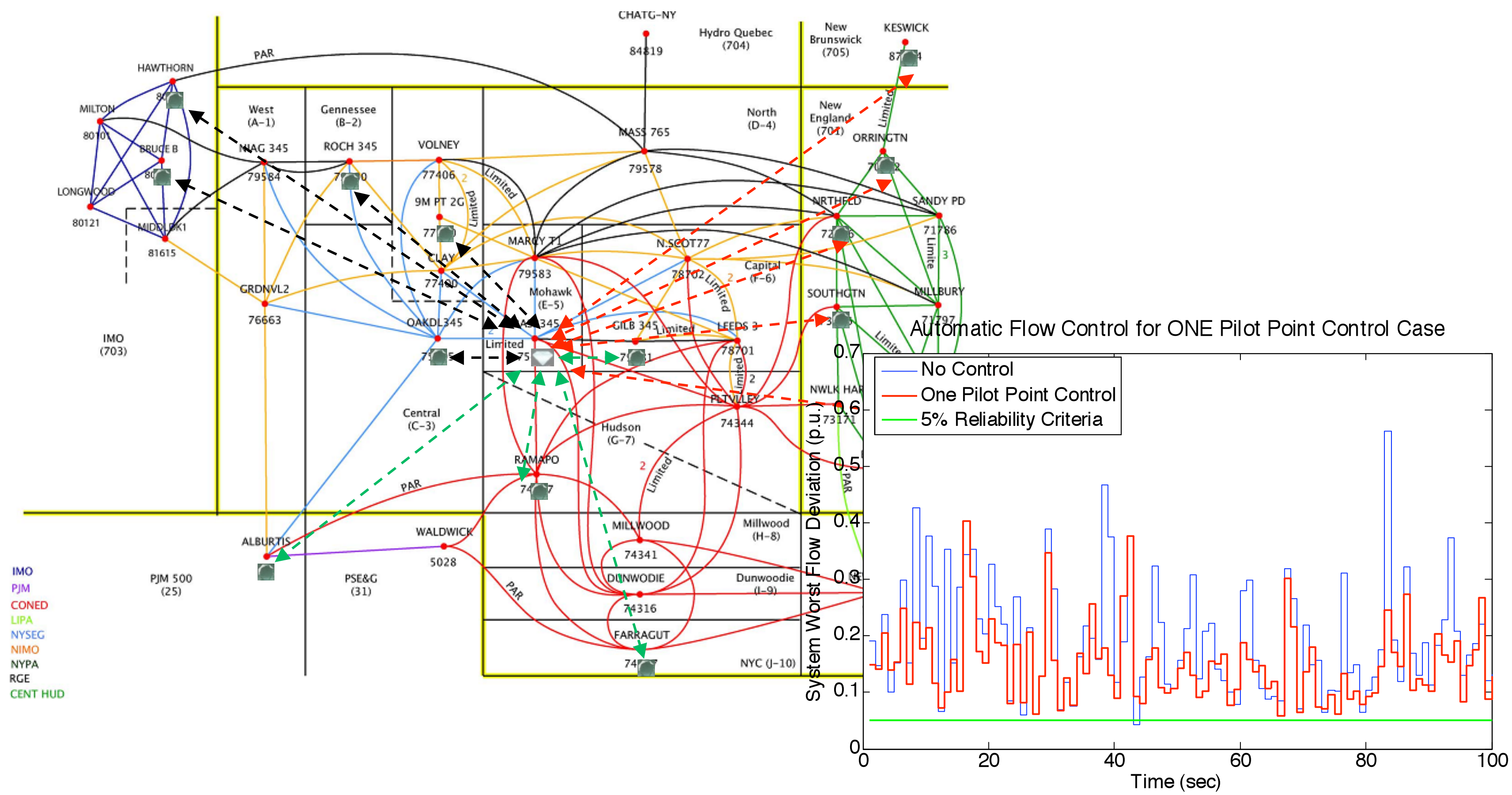
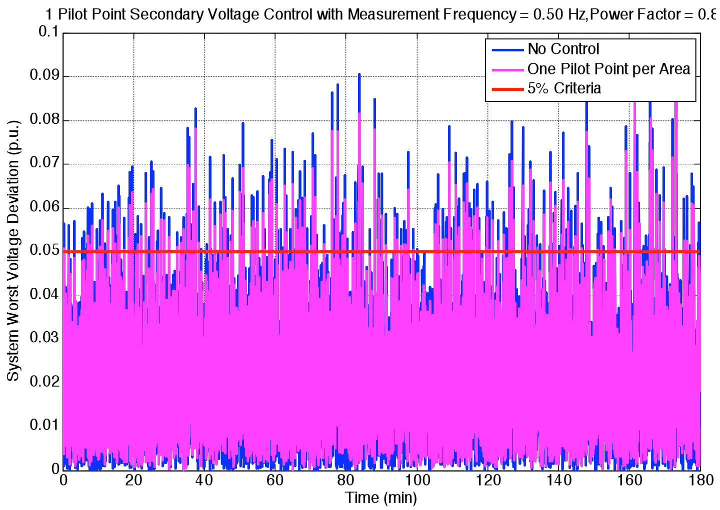
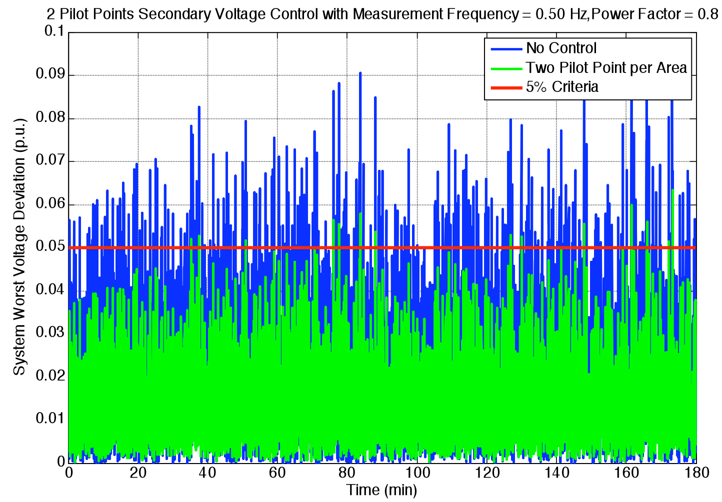
Pilot Point: Bus 75403



AVC for the NPCC with PMUs

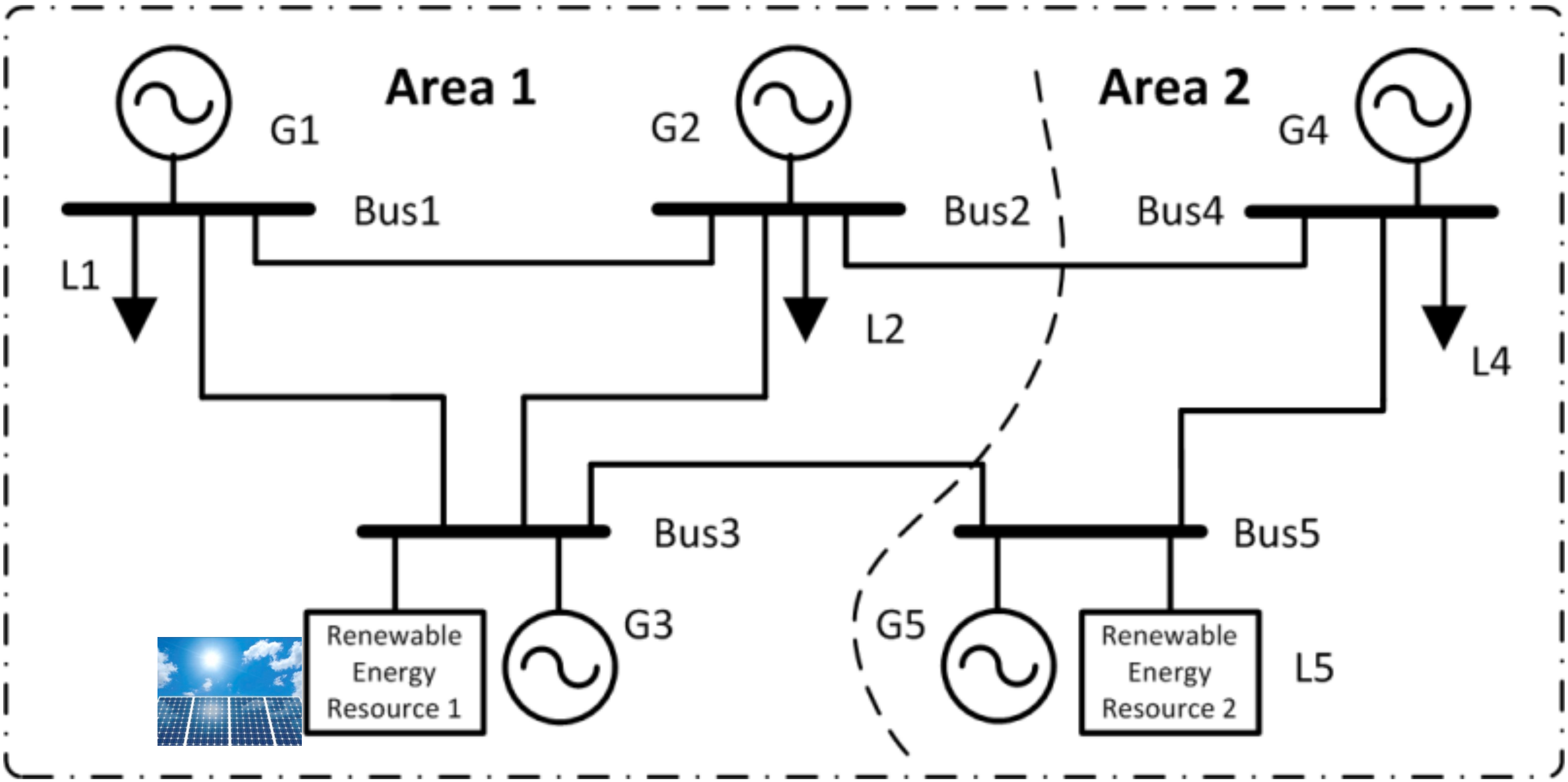
Simulations to show the worst voltage deviations in response to the reactive power load fluctuations (3 hours)





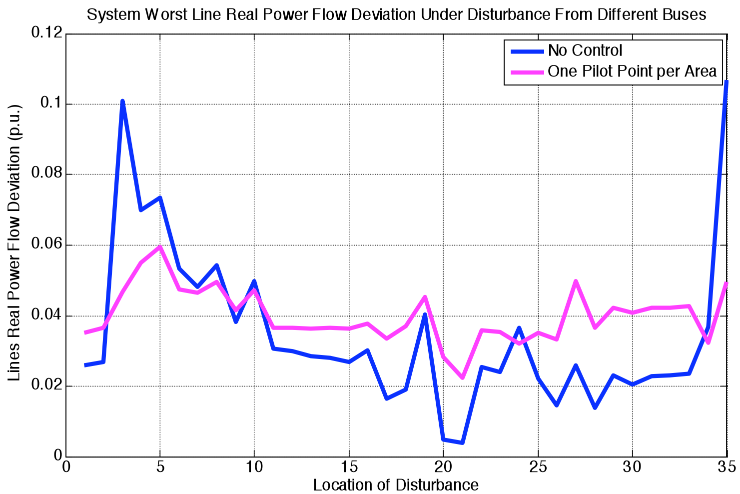
2 Pilot Points Control Performs Better Than 1 Pilot Point!

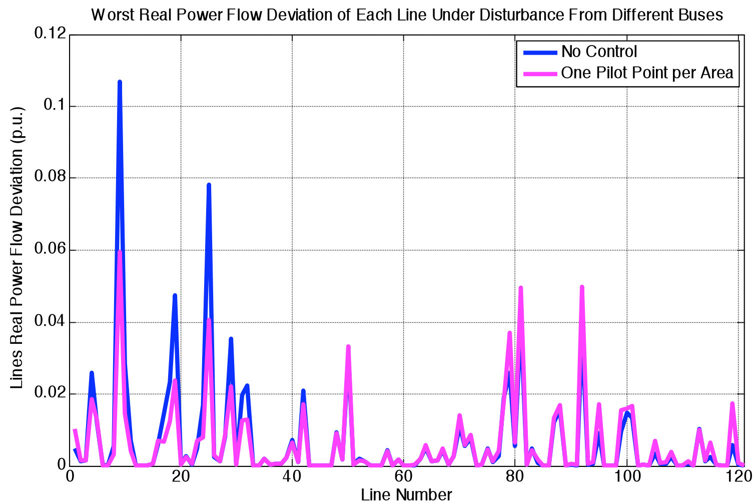
PMU-driven E-AGC for managing solar and wind deviation



E-AFC Using PMUs- NPCC System

Control real power disturbance



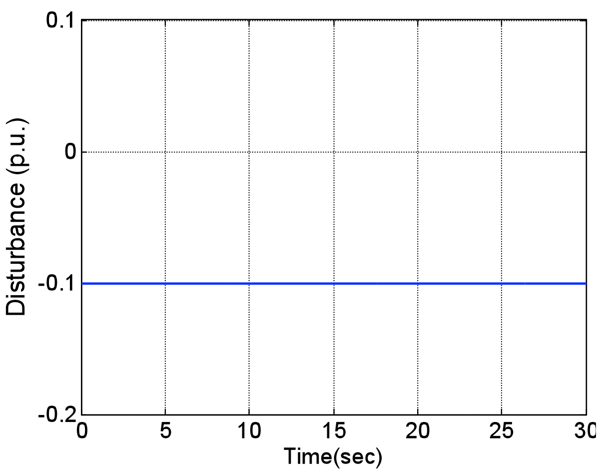


….Versions of AVC implemented in EdF Italy, China.. It may be time to consider by the US utilities

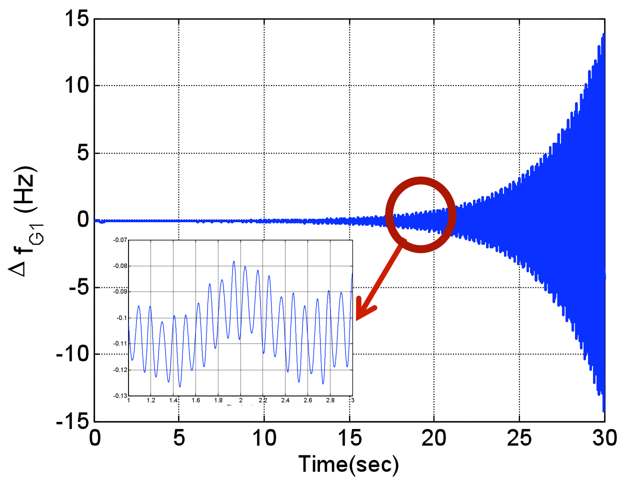
Liu and Ilic, "Toward PMU-Based Robust Automatic Voltage Control (AVC) and Automatic Flow Control (AFC)," IEEE PES, 2008

PMU-driven E-AGC for managing solar and wind deviation

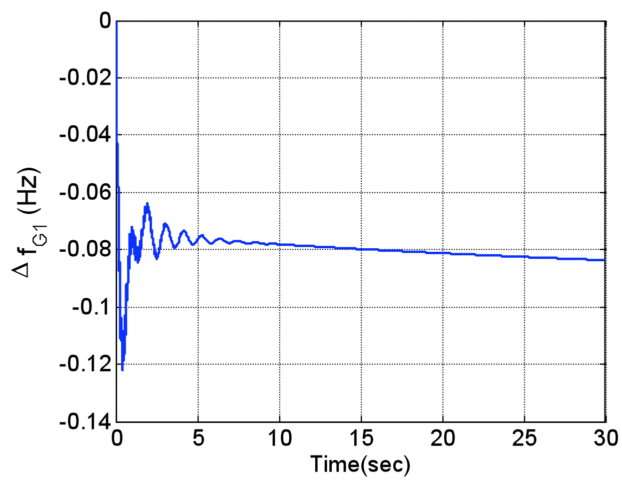
Areas 1 and 2: coupled by large reactance



Disturbances Injected from the Solar Power Resource

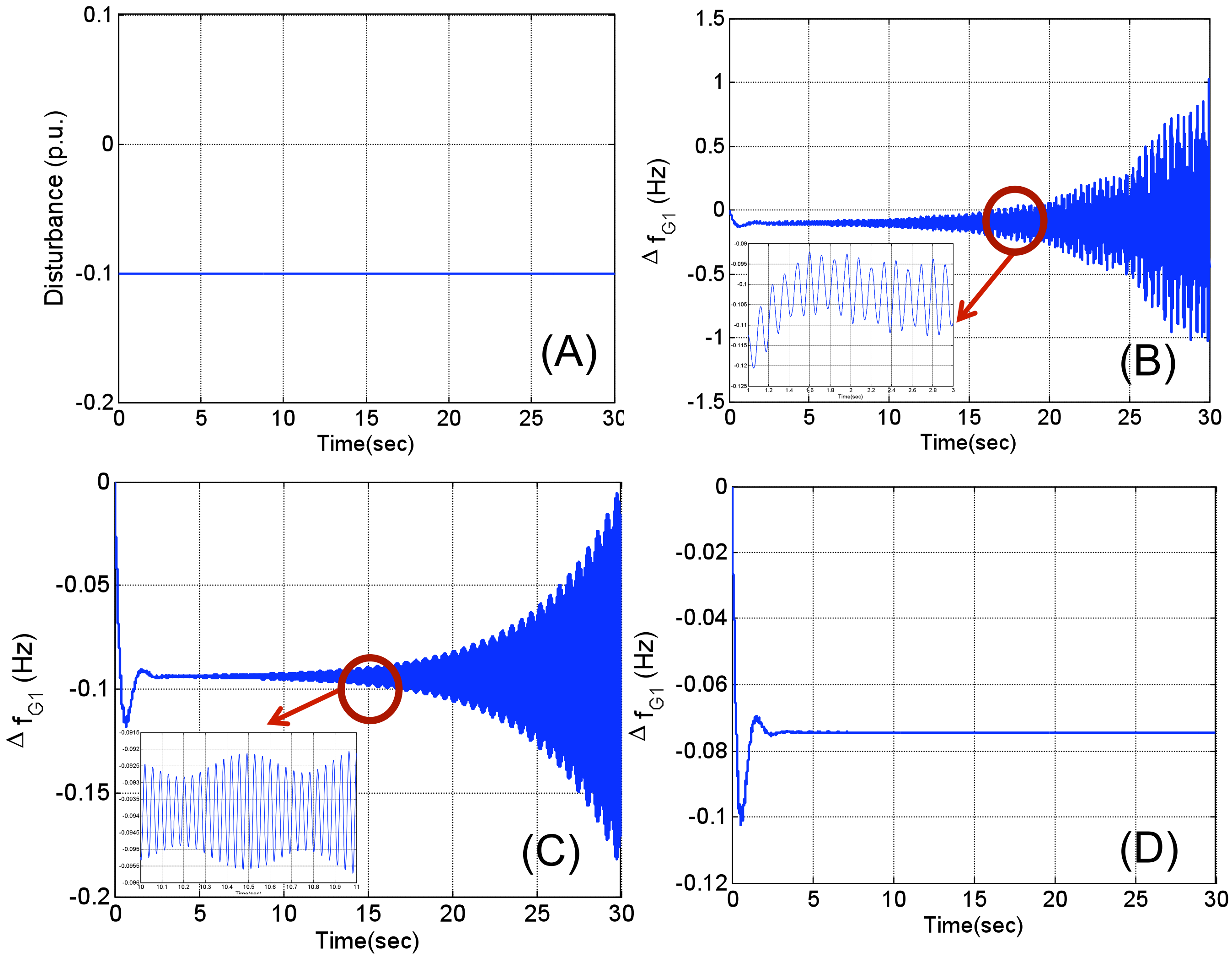


SBA-C locally stabilized (unstable, W-matrix condition for SBA-Cs unsatisfied)

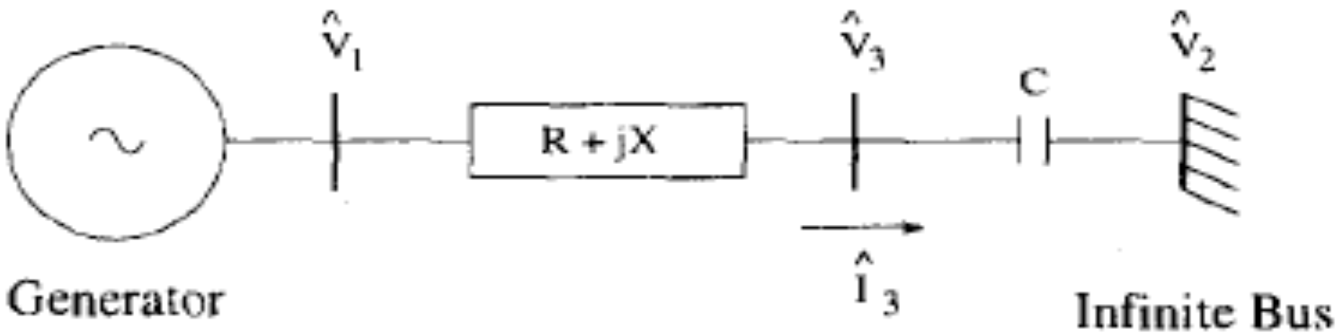


SBA-Cs' coupling minimized (stable, W-matrix for SBA-Rs satisfied)

E-AGC – strong interactions



The danger of system-wide instabilities



Network for subsynchronous resonance simulation.

System-wide fast interactions

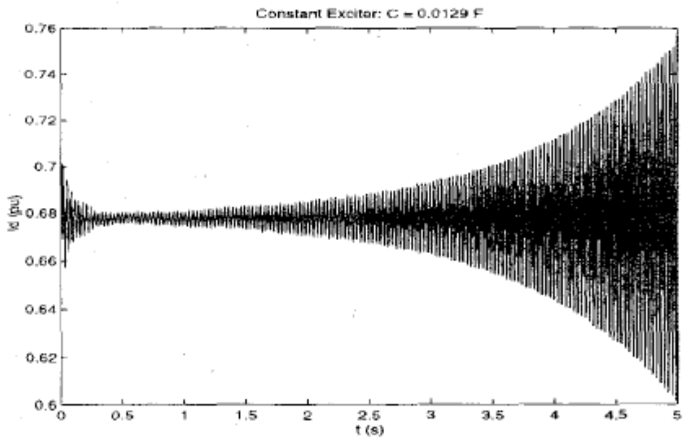


Fig. 16. Line current (real part of phasor) of a system experiencing subsynchronous resonance.

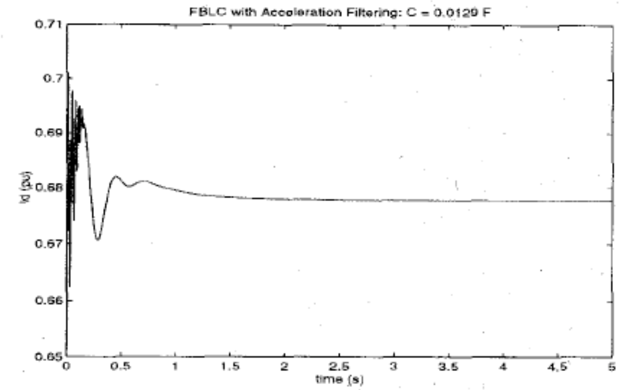


Fig. 19. Line current (real part of phasor) of a system with 23.0% compensation and FBLC with fourth-order Butterworth acceleration filtering.

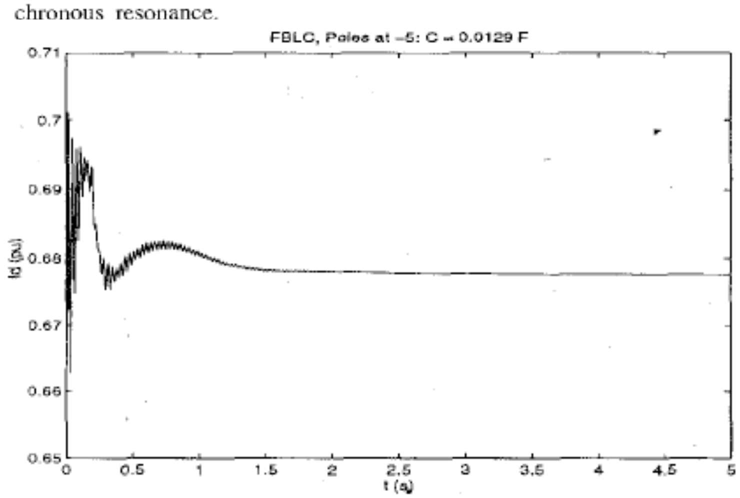


Fig. 17. Line current (real part of phasor) of a system with 23.0% compensation and FBLC.

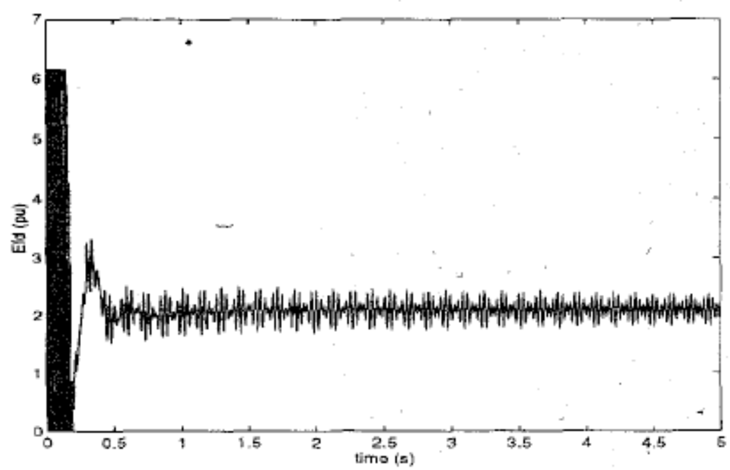
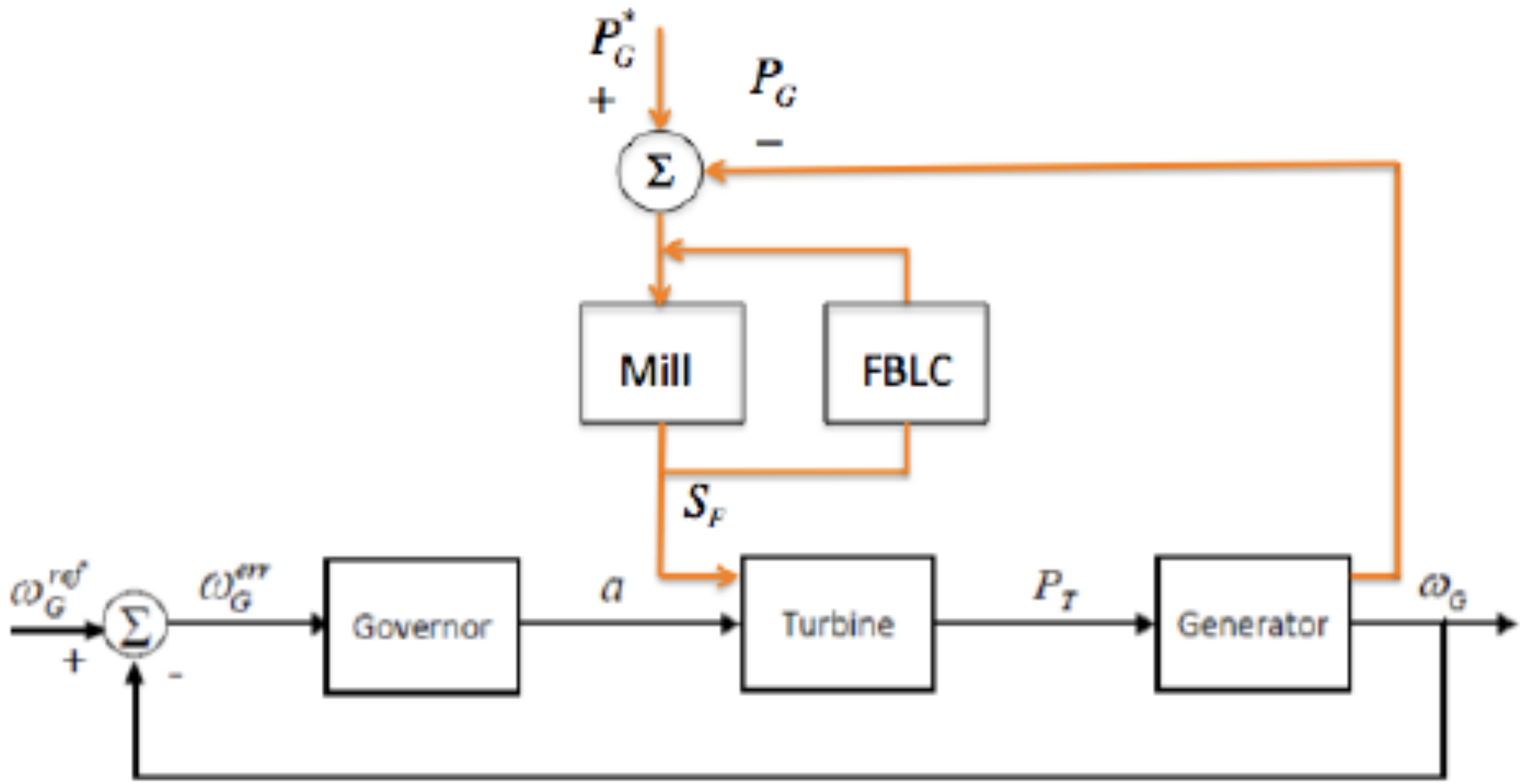


Fig. 20. Field voltage of a system with 23.0% compensation and FBLC with fourth-order Butterworth acceleration filtering.

Standards for provable dynamic performance?

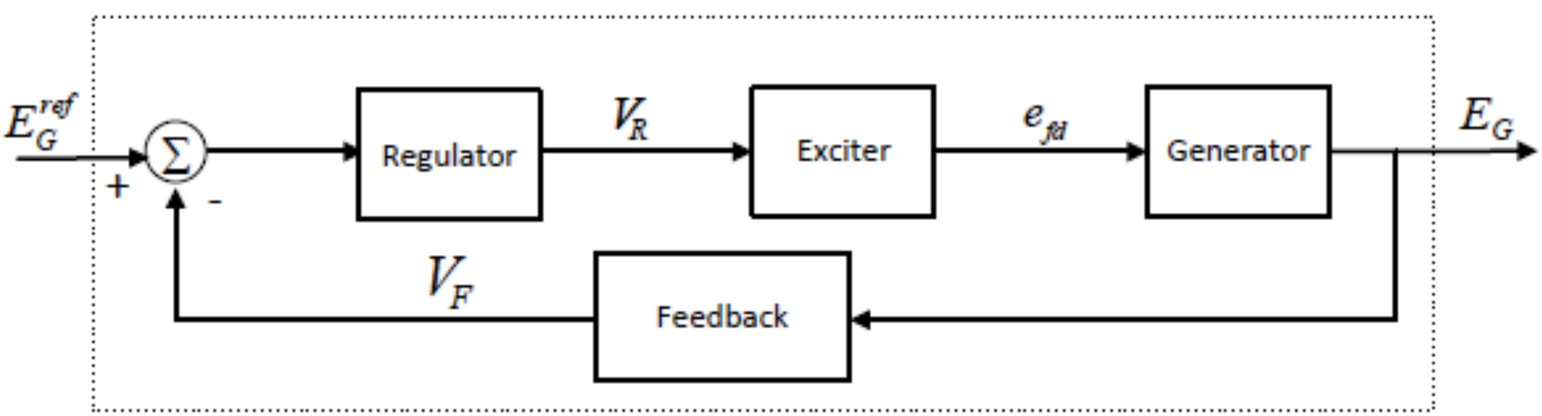
- Huge space for rethinking sensing, control, communications for large-scale systems
- Fundamentally nonlinear dynamic system--- the key role and opportunity to deploy what is already known (use of power electronics)
- Once closed-loop linear problem one can design much more efficient dynamic scheduling than currently used simplified (the question of ``ramp rate")

Power plant dynamics and its local control



FBLC-based Efd controller

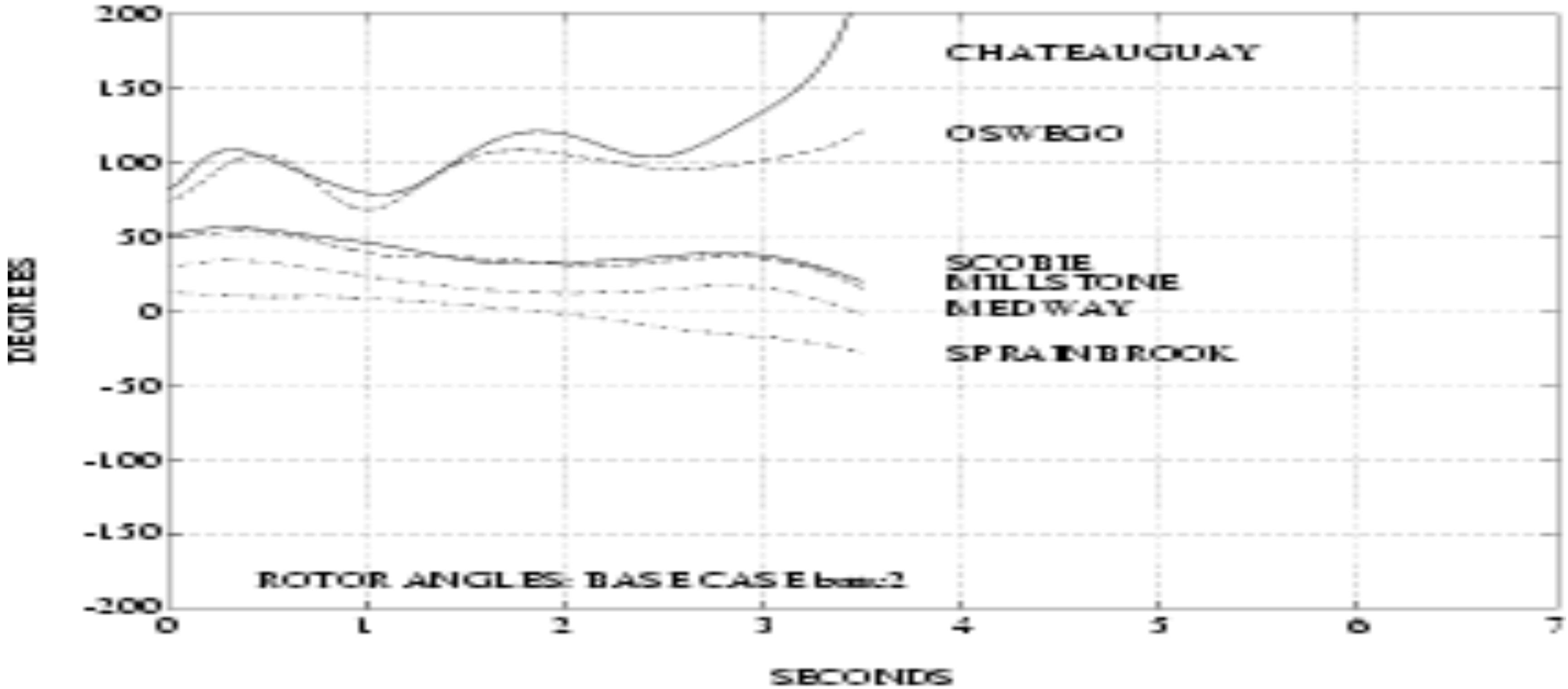
- Conventional power system stabilizer controls DC excitation Efd of the rotor winding in response to omega and E
- FBLC-based Efd control responds to acceleration



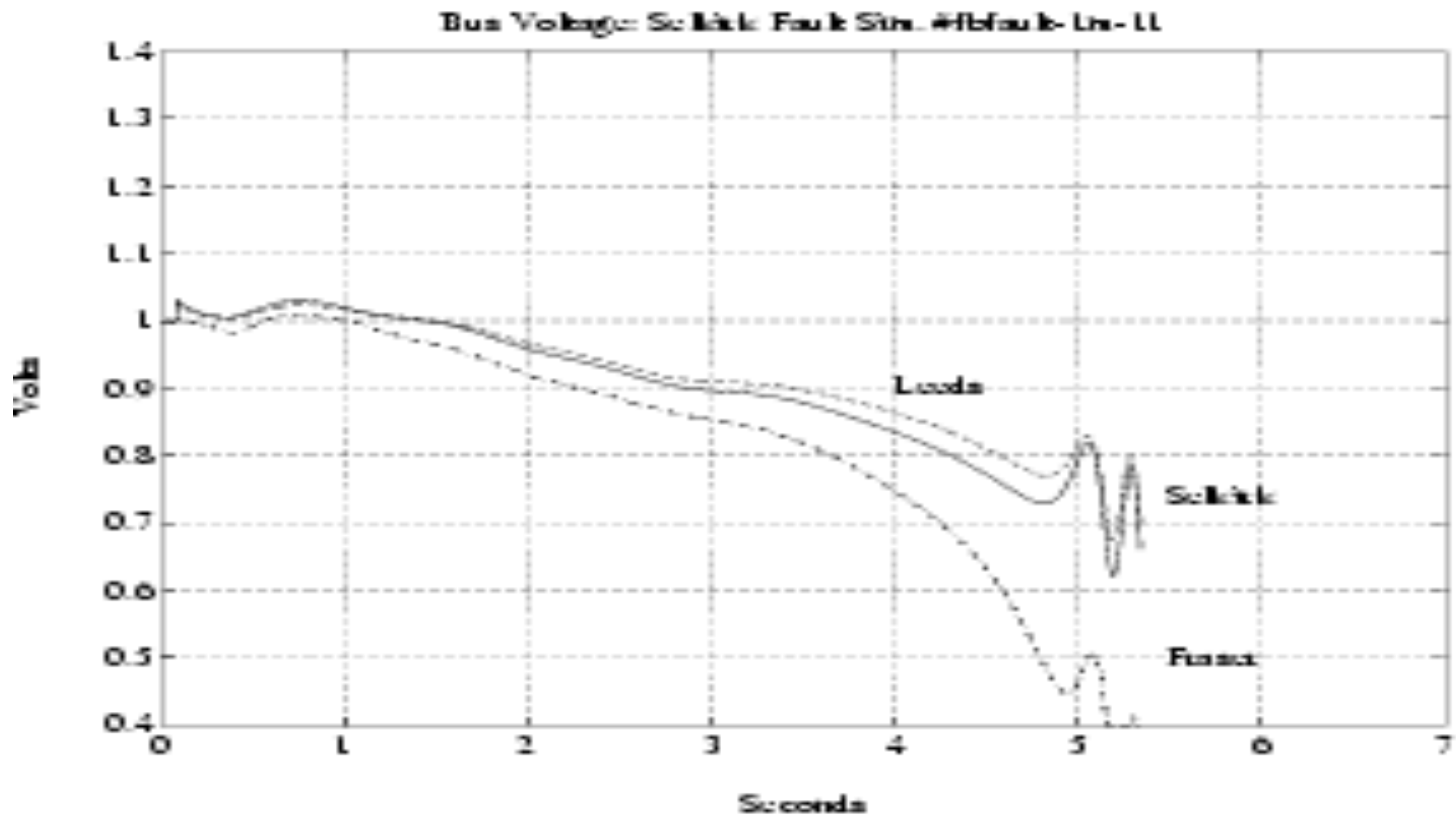
The role of FBLC control in preventing blackouts

- A 38-node, 29 machine dynamic model of the NPCC system
- A multi-machine oscillation occurred at .75Hz, involving groups of machines in NYC and the northeastern part of New York State, as well as parts of Canadian power system;
- 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 failure of Oswego unit.

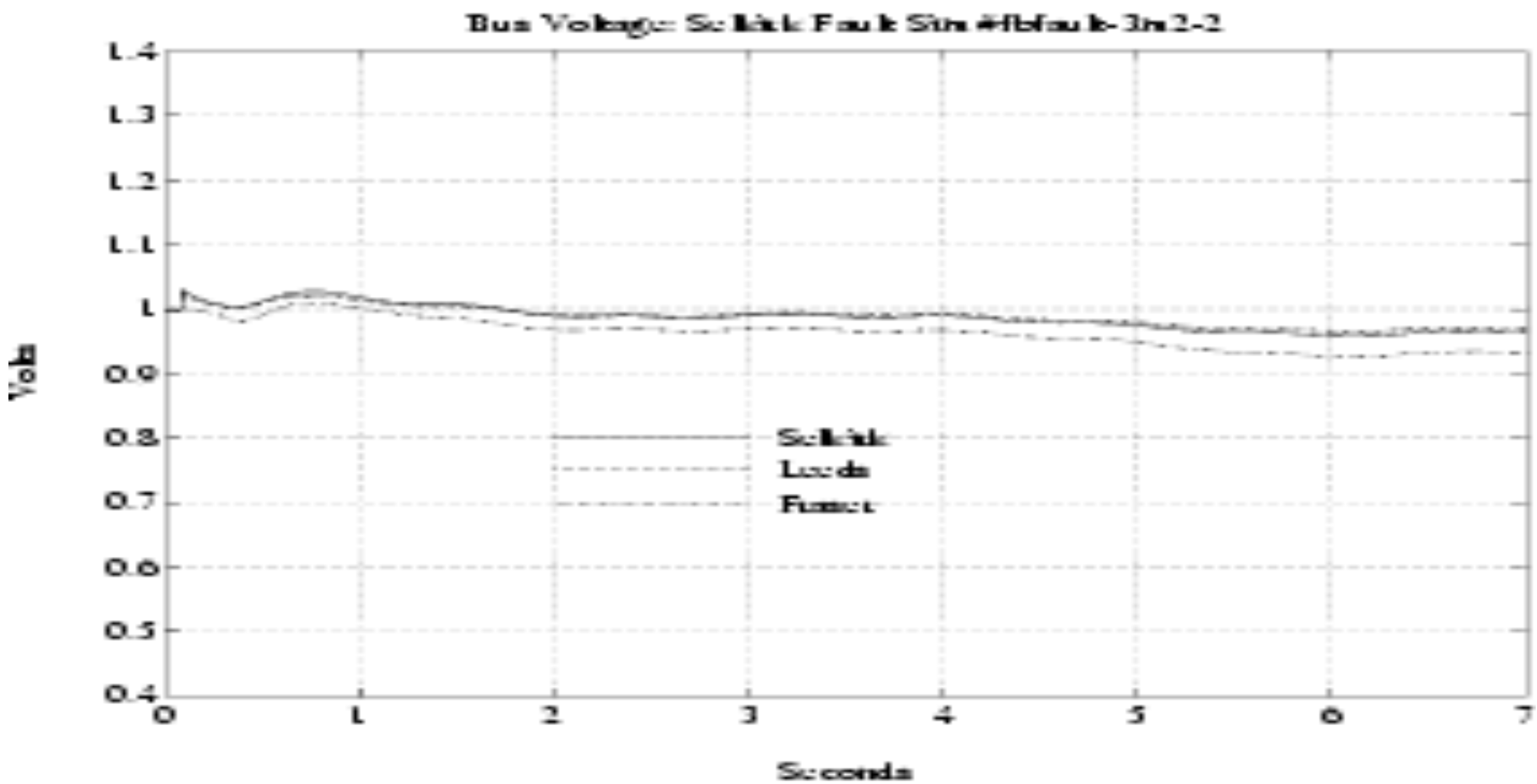
Rotor angles -- base case for Selkrik fault with conventional controller



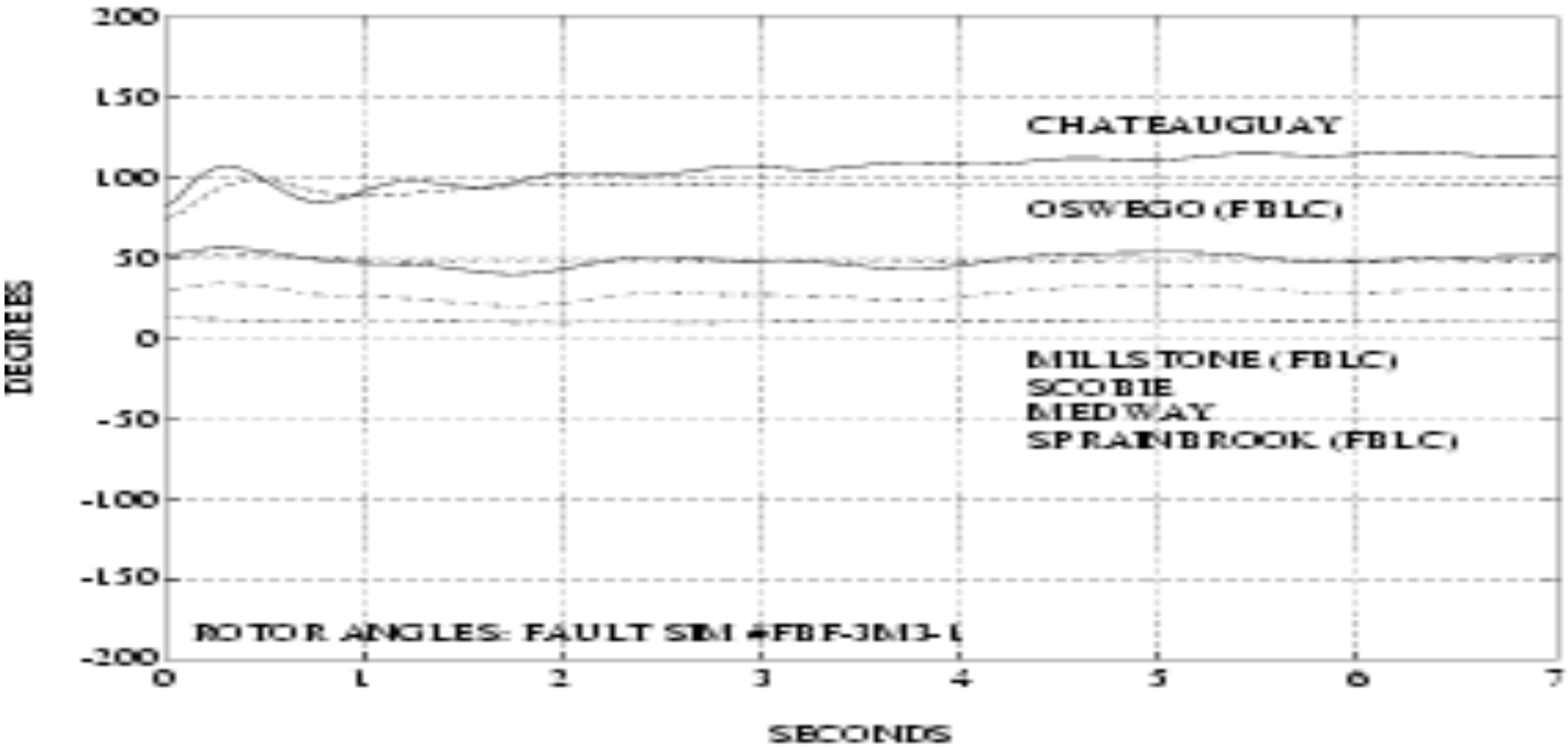
Voltage response with conventional controllers-base case Selkrik fault



Bus voltages with new controllers

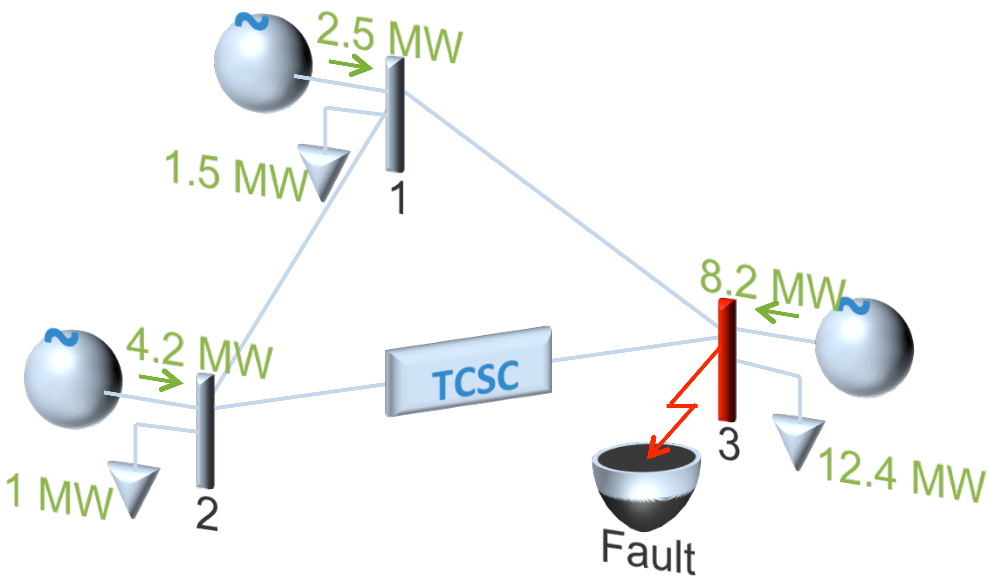


Rotor angle response with local nonlinear controllers--an early example of flat control design



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

Nonlinear control for storage devices (FACTS,flywheels)



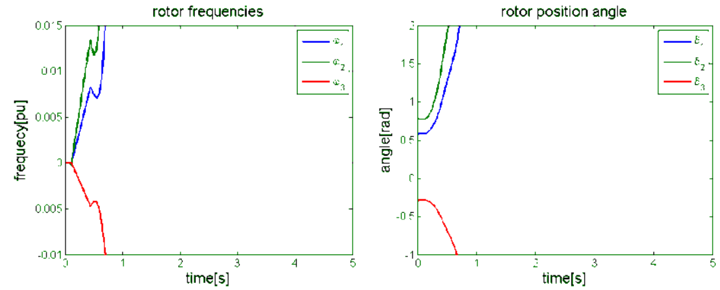
Fault:

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

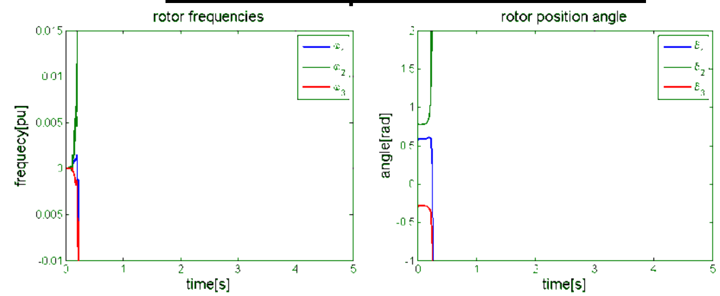
Critical clearing time:

$$T_{CCT} = 0.25s$$

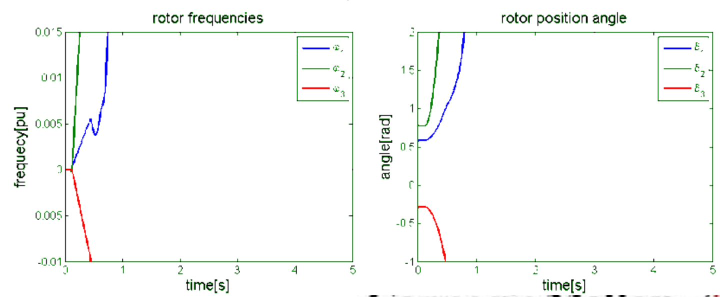
No controller on TCSC



Linear PI power controller[2]

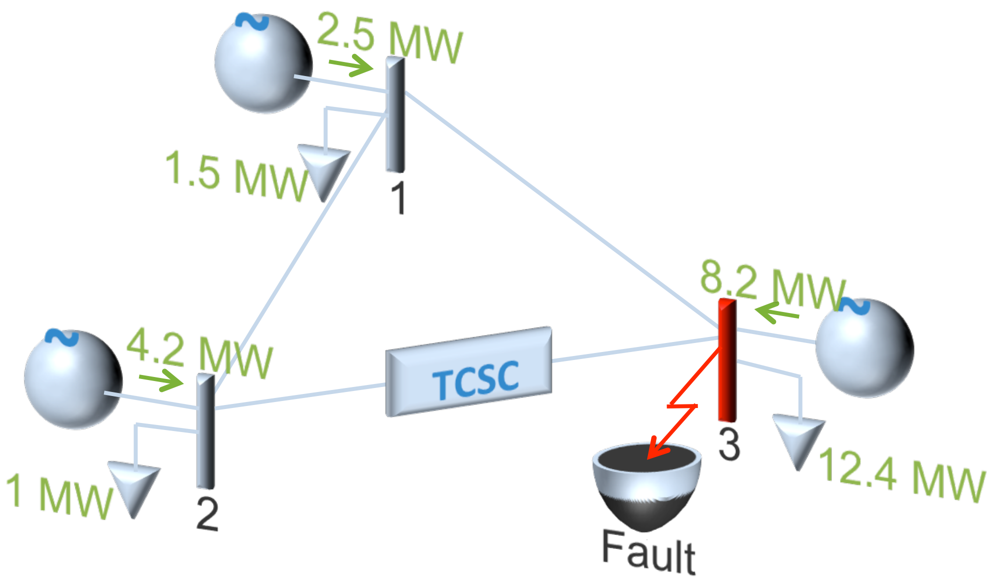


Nonlinear Lyapunov controller[3]

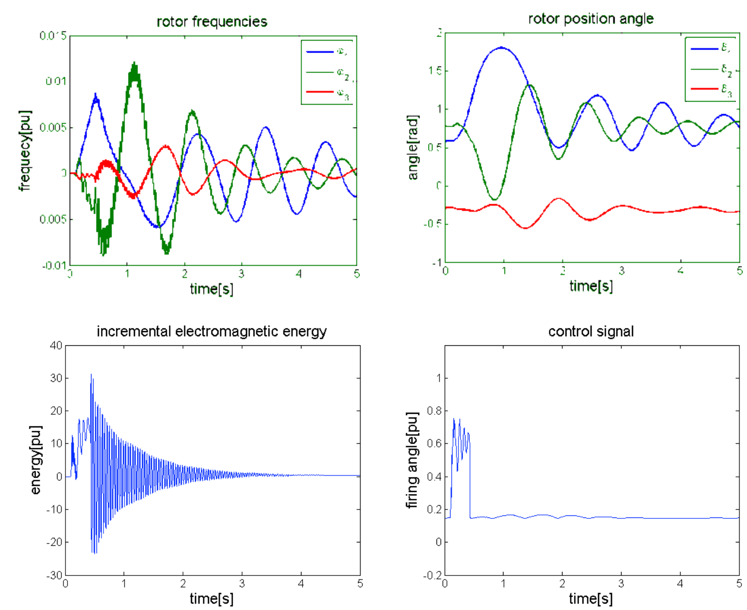


[1] The test system: J. W. Chapman, *"Power System Control for Large Disturbance Stability: Security, Robustness and Transient Energy"*, Ph.D. Thesis: Massachusetts Institute of Technology, 1996.
[2] Linear controller: L. Angquist, C. Gama, *"Damping Algorithm Based on Phasor Estimation"*, IEEE Power Engineering Society Winter Meeting, 2001
[3] Nonlinear controller: M. Ghandhari, G. Andersson, I. Hiskens, *"Control Lyapunov Function for Controllable Series Devices"*, IEEE Transactions on Power Systems, 2001, vol. 16, no. 4, pp. 689-694

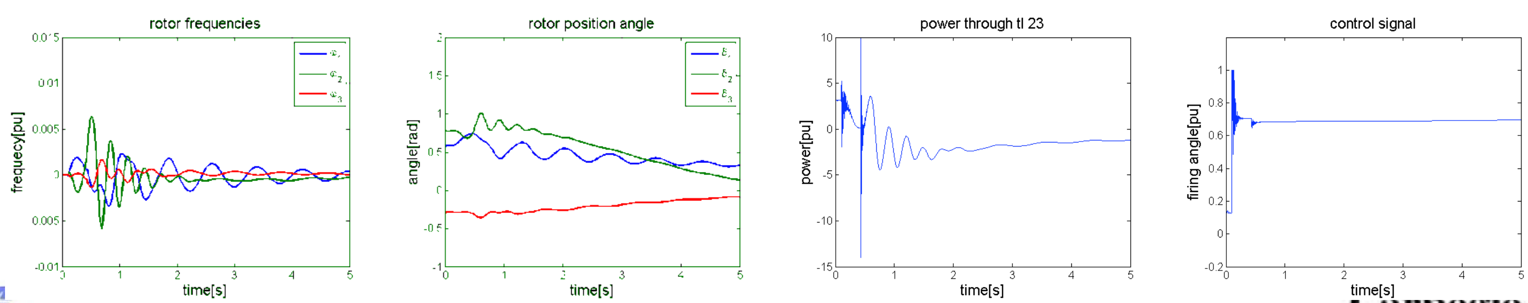
Use of interaction variables in strongly coupled systems



Interaction variable choice 1:



Interaction variable choice 2:



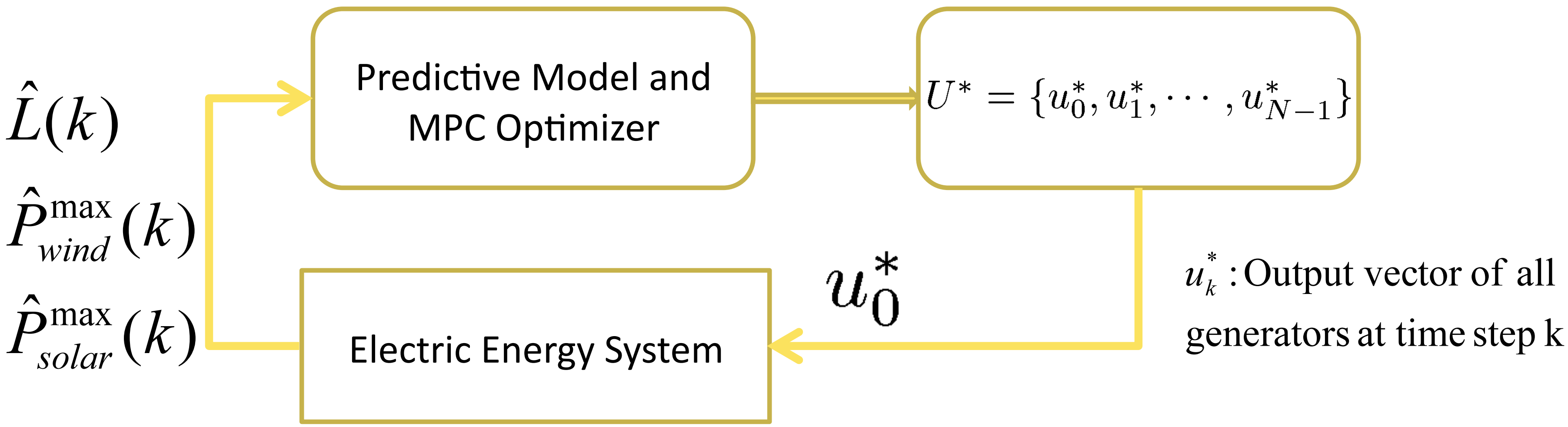
FBLC--The major promise for plug-and play realistic decentralized sensors and controllers

- Embedded FBLC with right sensors and filters makes the closed-loop dynamics simple (linear)
- Shown to cancel dynamic interactions between the components
- Increased number and types of fast controllers (from PSS on generators, to a mix with VSD of dispersed loads (for efficiency) ; power-electronically controlled reactive storage devices –FACTS; power electronically controlled small dispersed storage –flywheels)
- We are working on ``standards for dynamics" in future electric energy systems (w/o the promise of FBLC hard to make them provable)

Minimally coordinated self-dispatch—DyMonDS

- Distributed management of temporal interactions of resources and users
- Different technologies perform look-ahead predictions and optimize their expected profits given system signal (price or system net demand); they create bids and these get cleared by the (layers of) coordinators
- Putting Auctions to Work in Future Energy Systems
- DyMonDS-based simulator of near-optimal supply-demand balancing in an energy system with wind, solar, conventional generation, elastic demand, and PHEVs.

Centralized MPC –Benchmark



- 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.

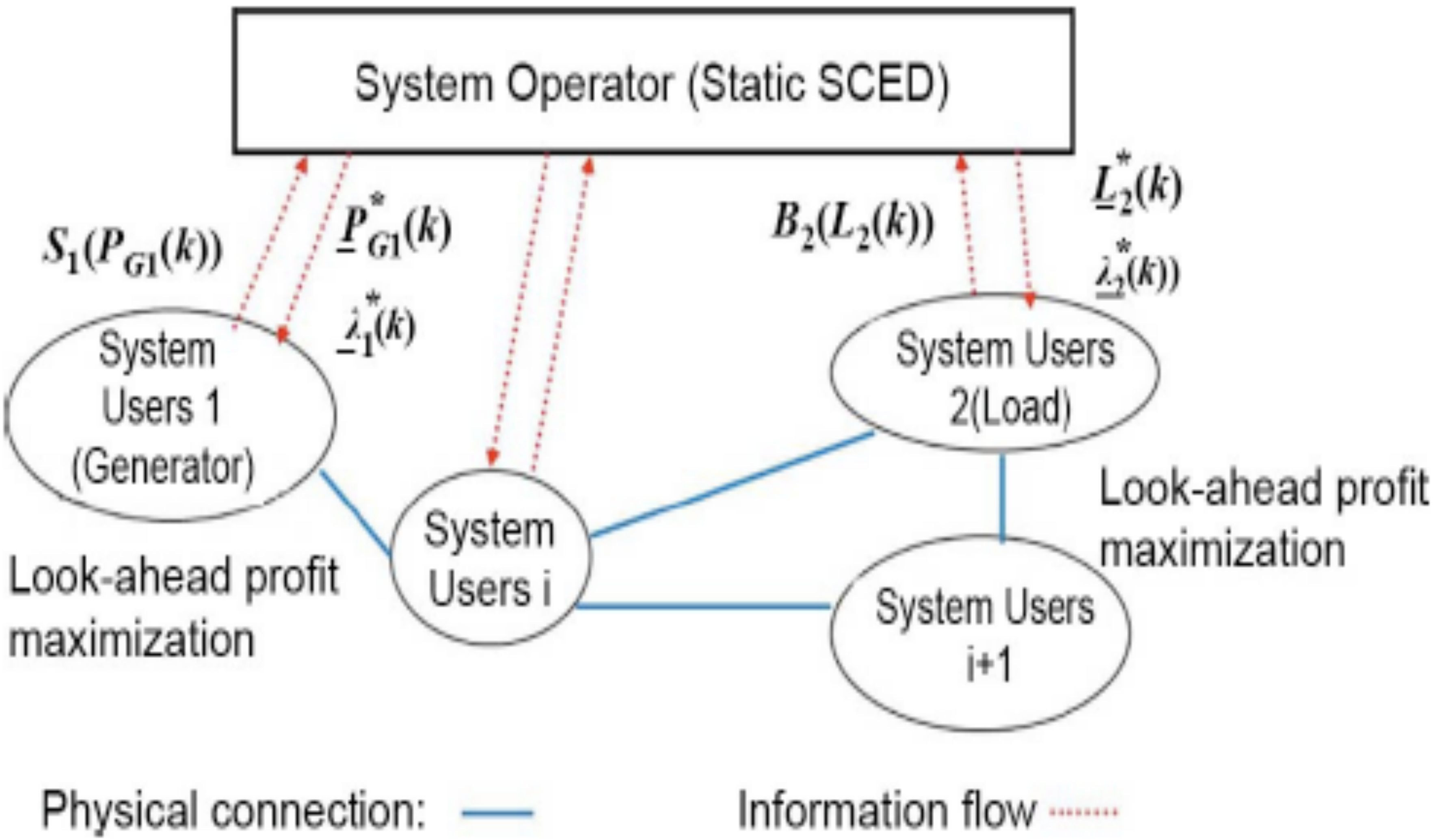
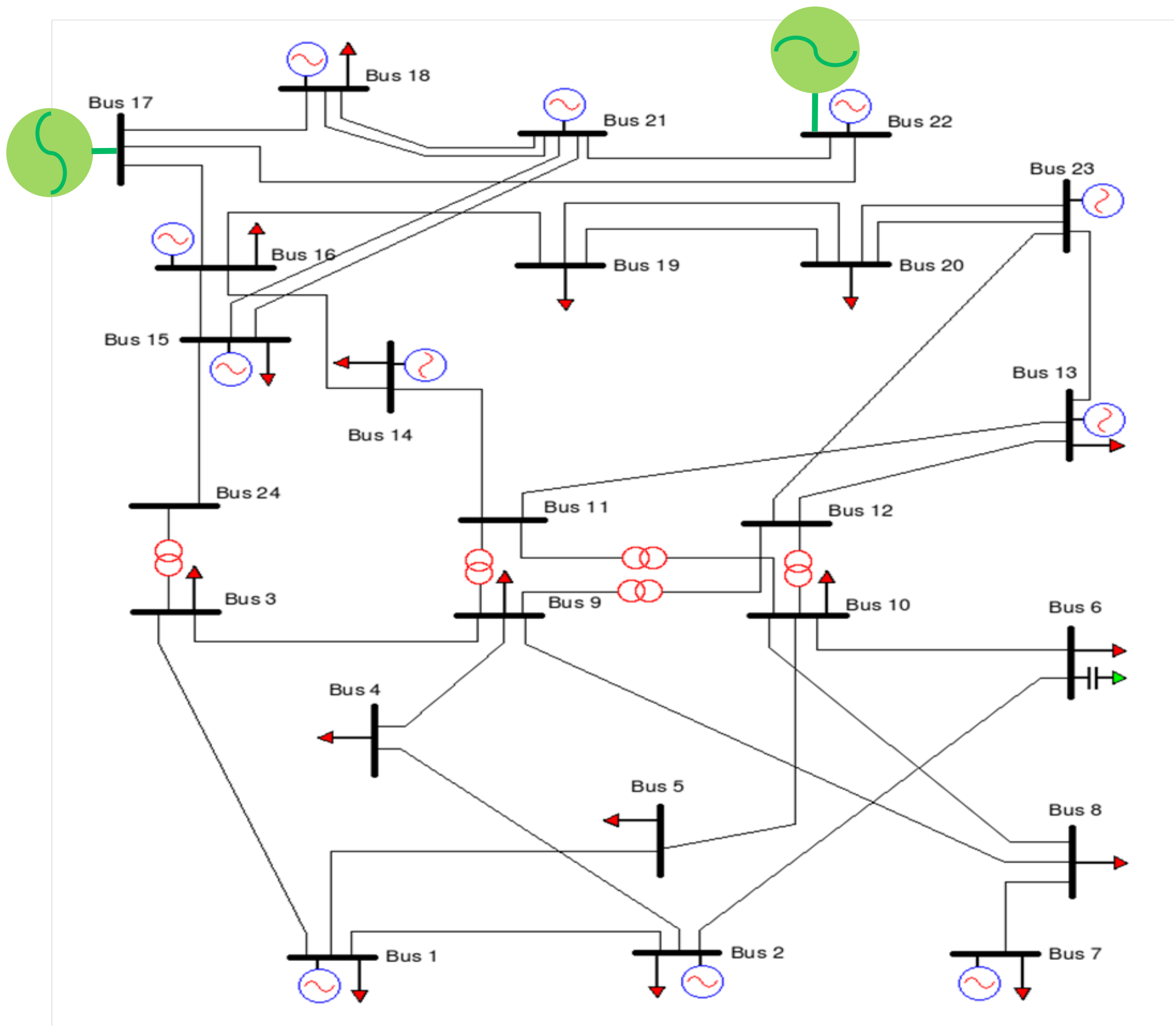


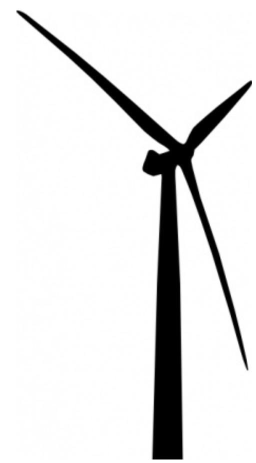
Fig. 3. Required information exchange for DYMONDS-based dispatch.

End-to-end CPS for evolving SEES (Architectures 2-5)

- Performance objectives very different (obtained in an interactive ways)
- DYMONDS simulator (proof-of-concept)
- Azores islands (San Miguel different challenge than Flores)
- Possible to design cyber for low-cost green architectures 2-5

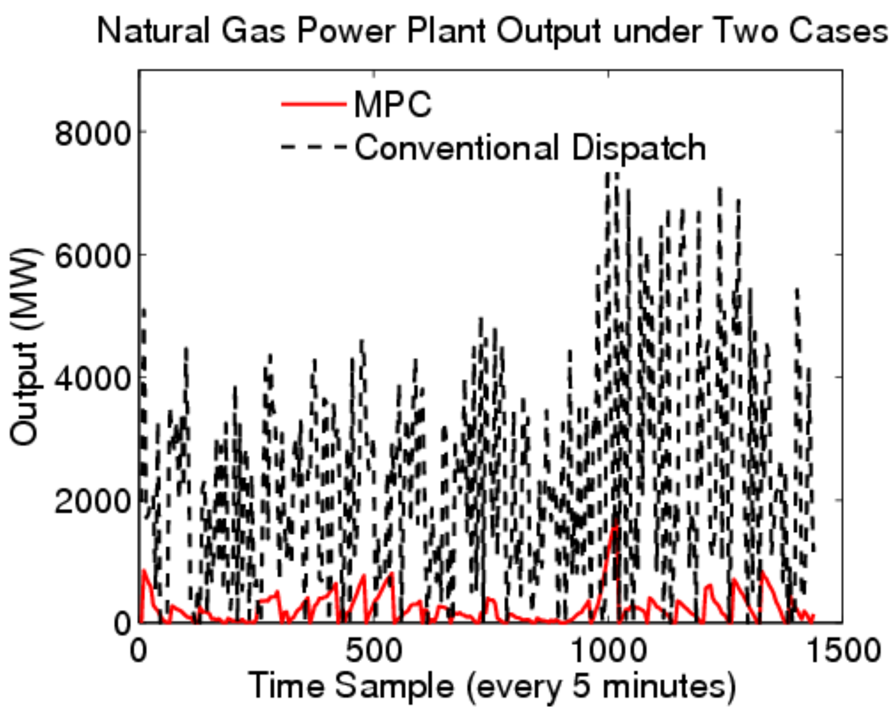
DYMONDS Simulator
IEEE RTS with Wind Power

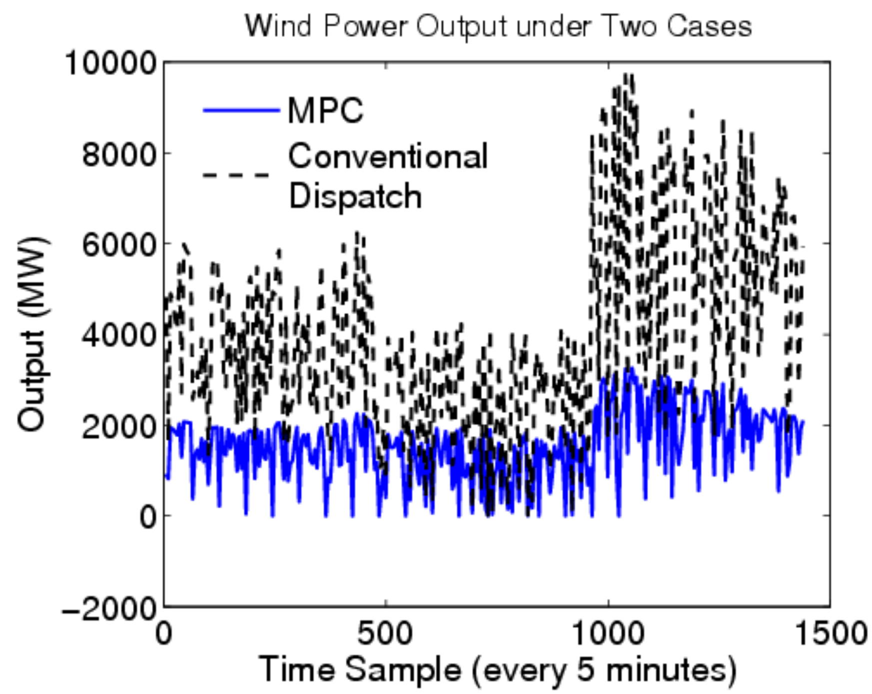




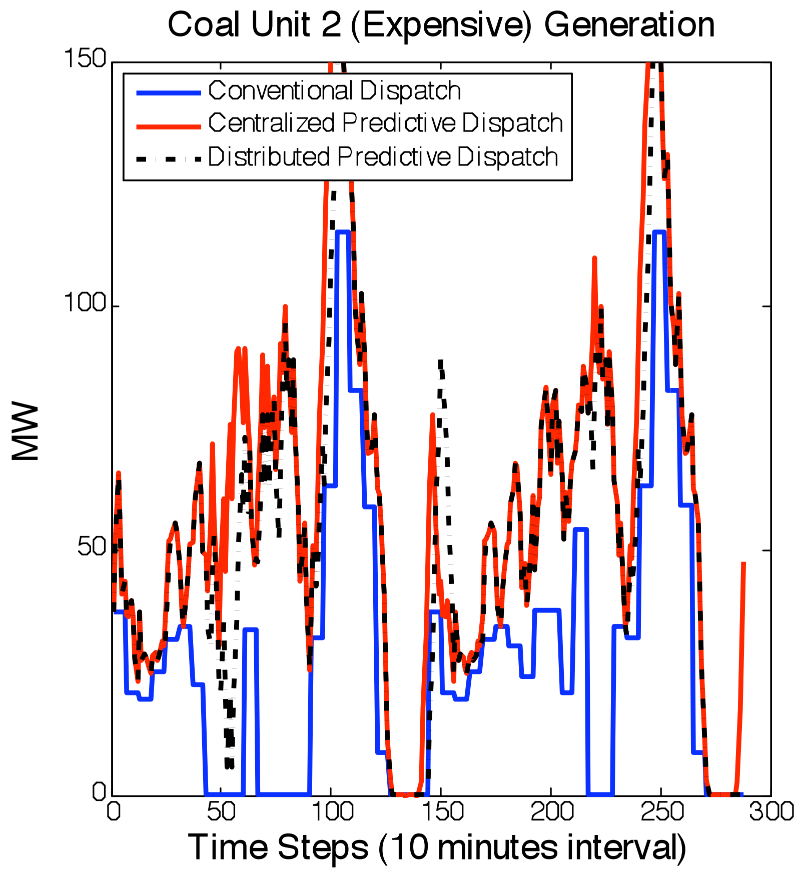
❖ 20% / 50% penetration to the system [2]

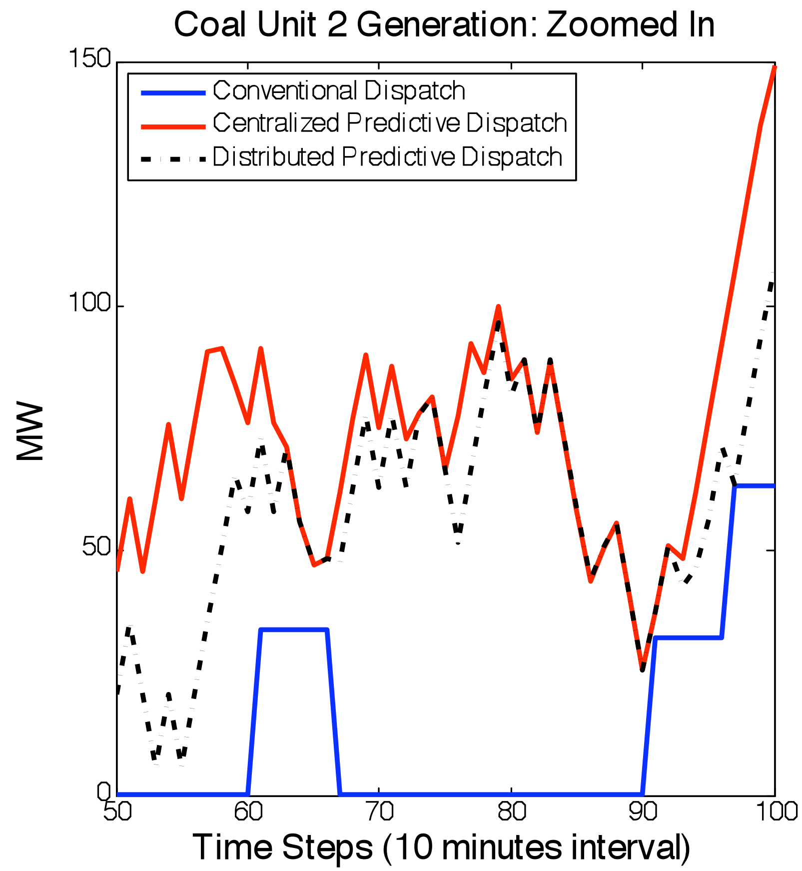
Conventional cost over 1 year *	Proposed cost over the year	Difference	Relative Saving
$ 129.74 Million	$ 119.62 Million	$ 10.12 Million	7.8%





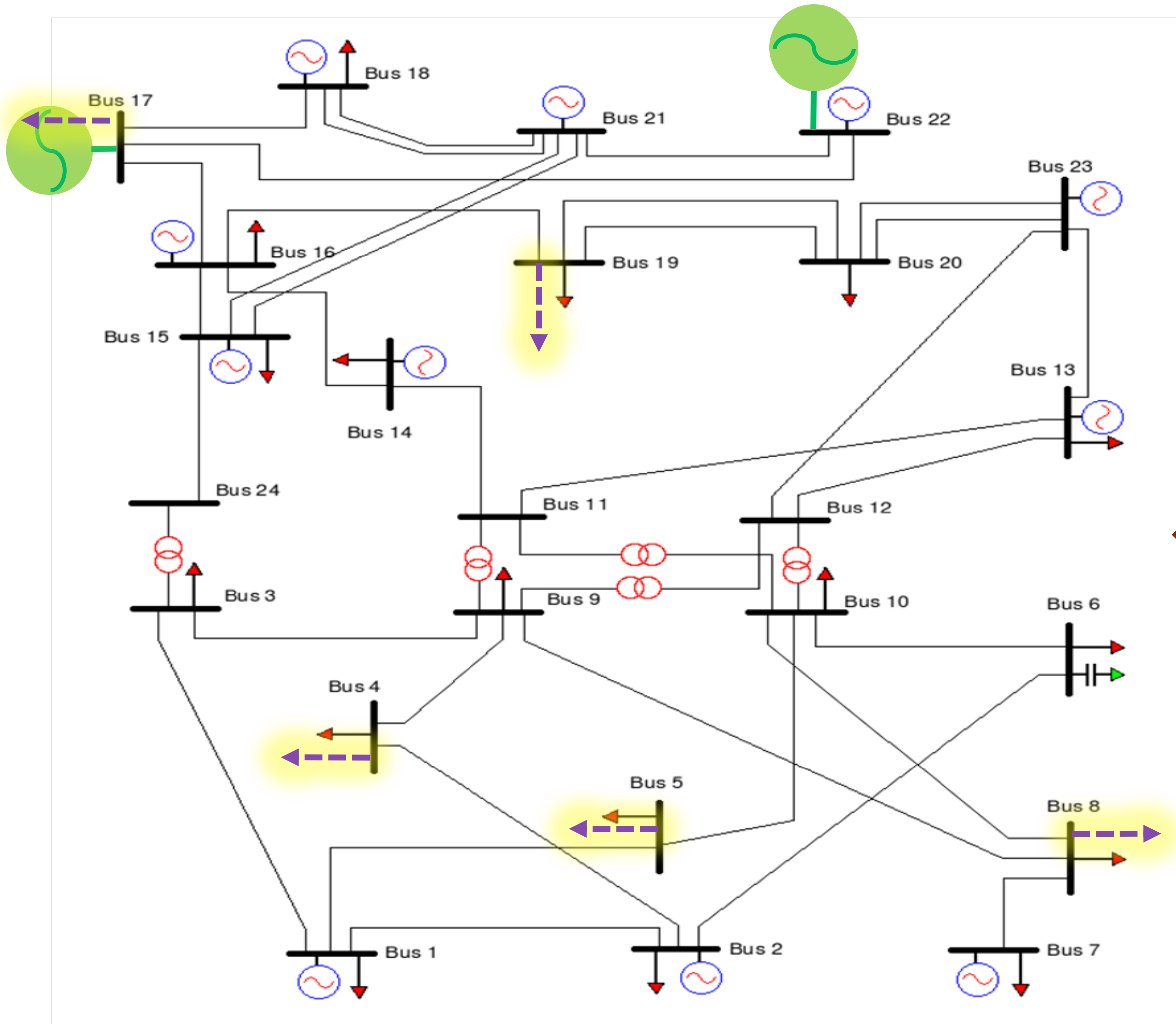
*: load data from New York Independent System Operator, available online at: http://www.nyiso.com/public/market_data/load_data.jsp

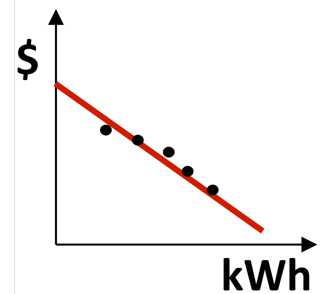




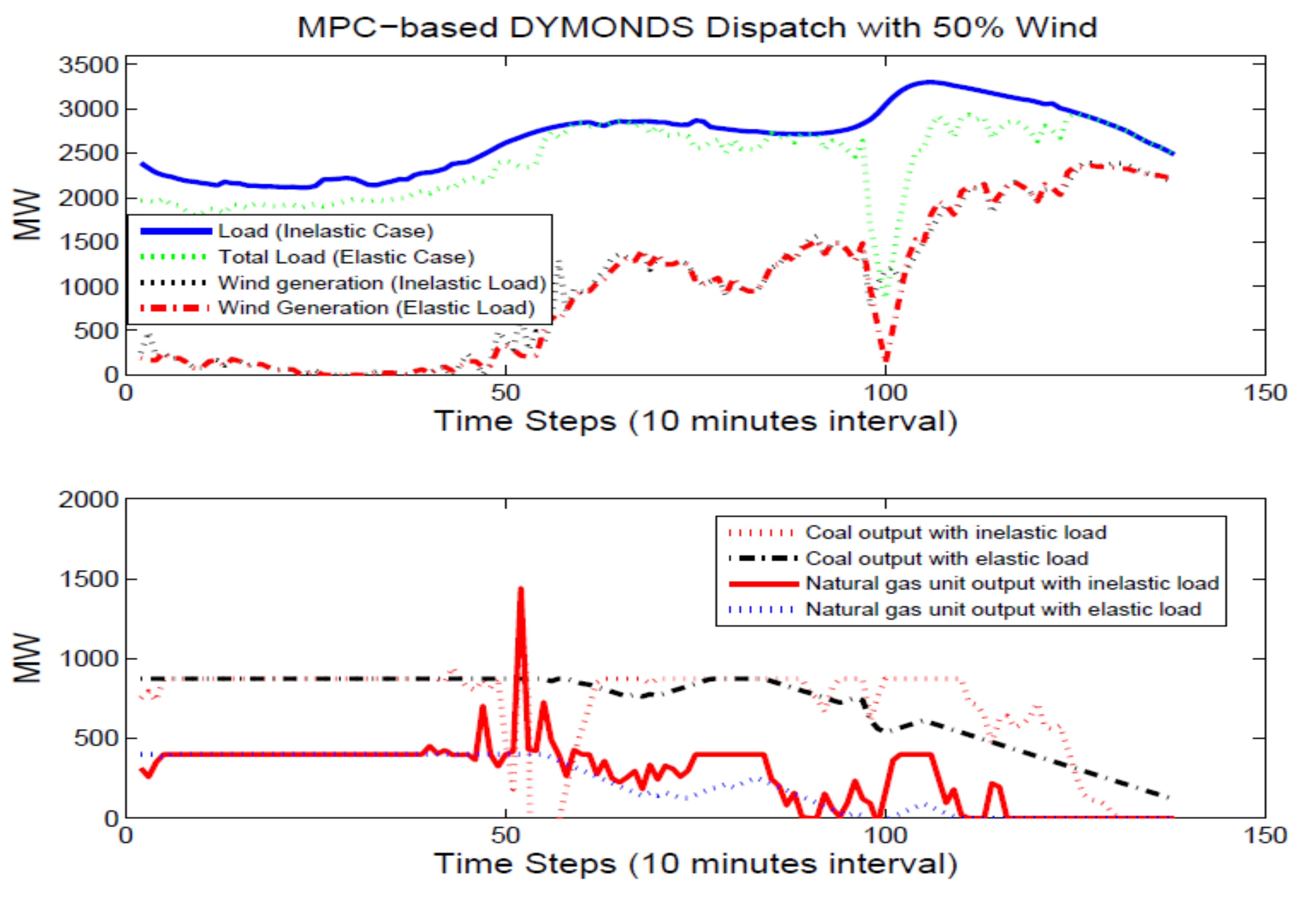
BOTH EFFICIENCY AND RELIABILITY MET

DYMONDS Simulator
Impact of price-responsive demand

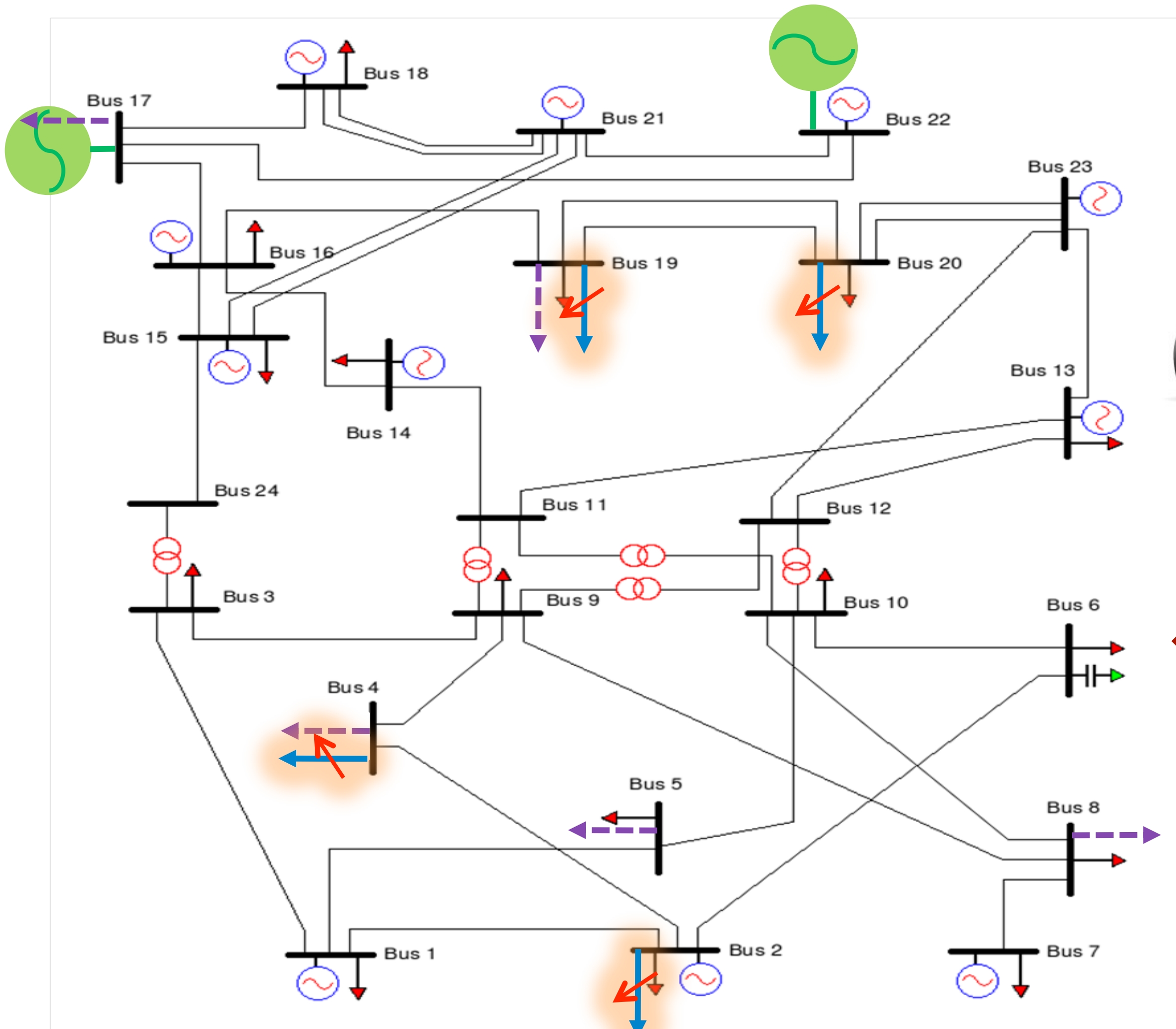




- Elastic demand that responds to time-varying prices

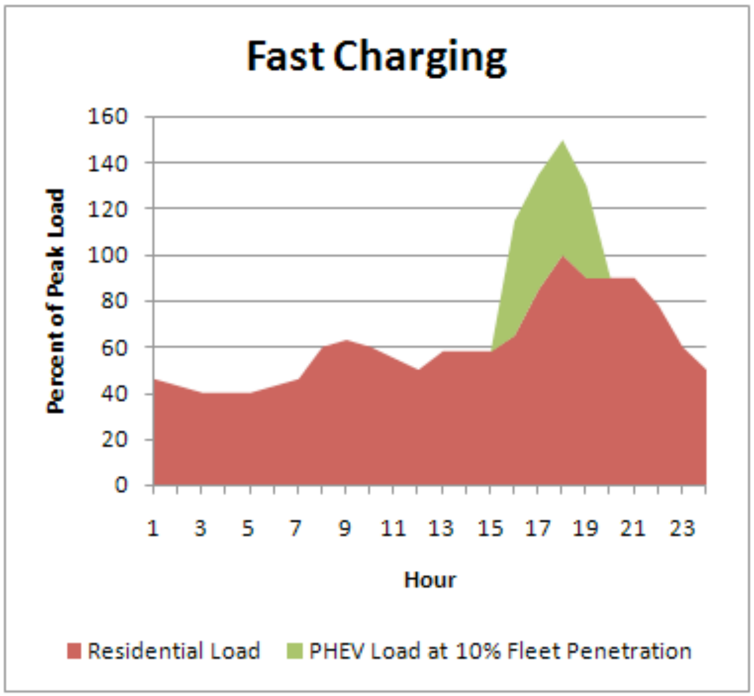

MPC−based DYMONDS Dispatch with 50% Wind
3500
3000
2500
2000
1500
1000
500
0
MW
0
50
100
150
Time Steps (10 minutes interval)
Load (Inelastic Case)
Total Load (Elastic Case)
Wind generation (Inelastic Load)
Wind Generation (Elastic Load)
2000
1500
1000
500
0
MW
0
50
100
150
Time Steps (10 minutes interval)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

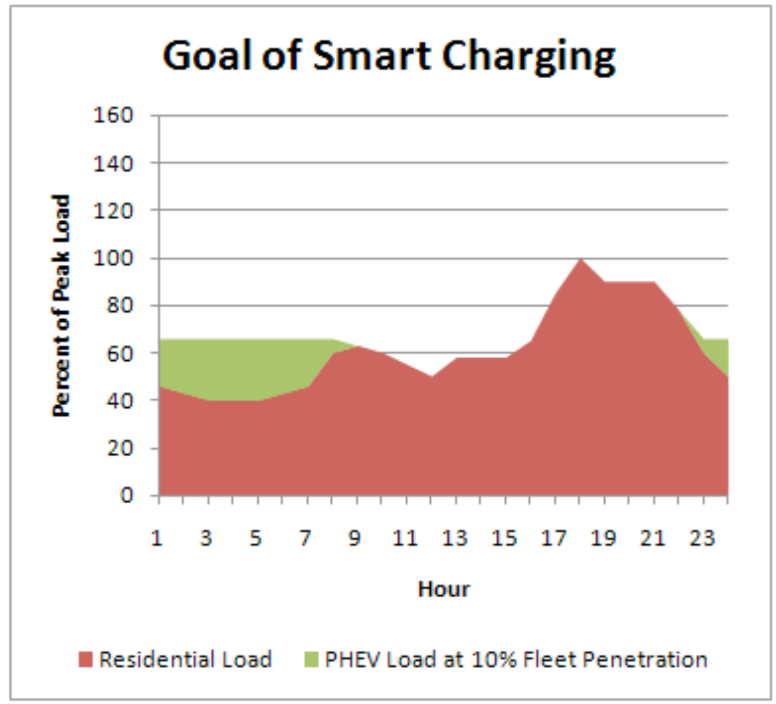
DYMONDS Simulator
Impact of Electric vehicles

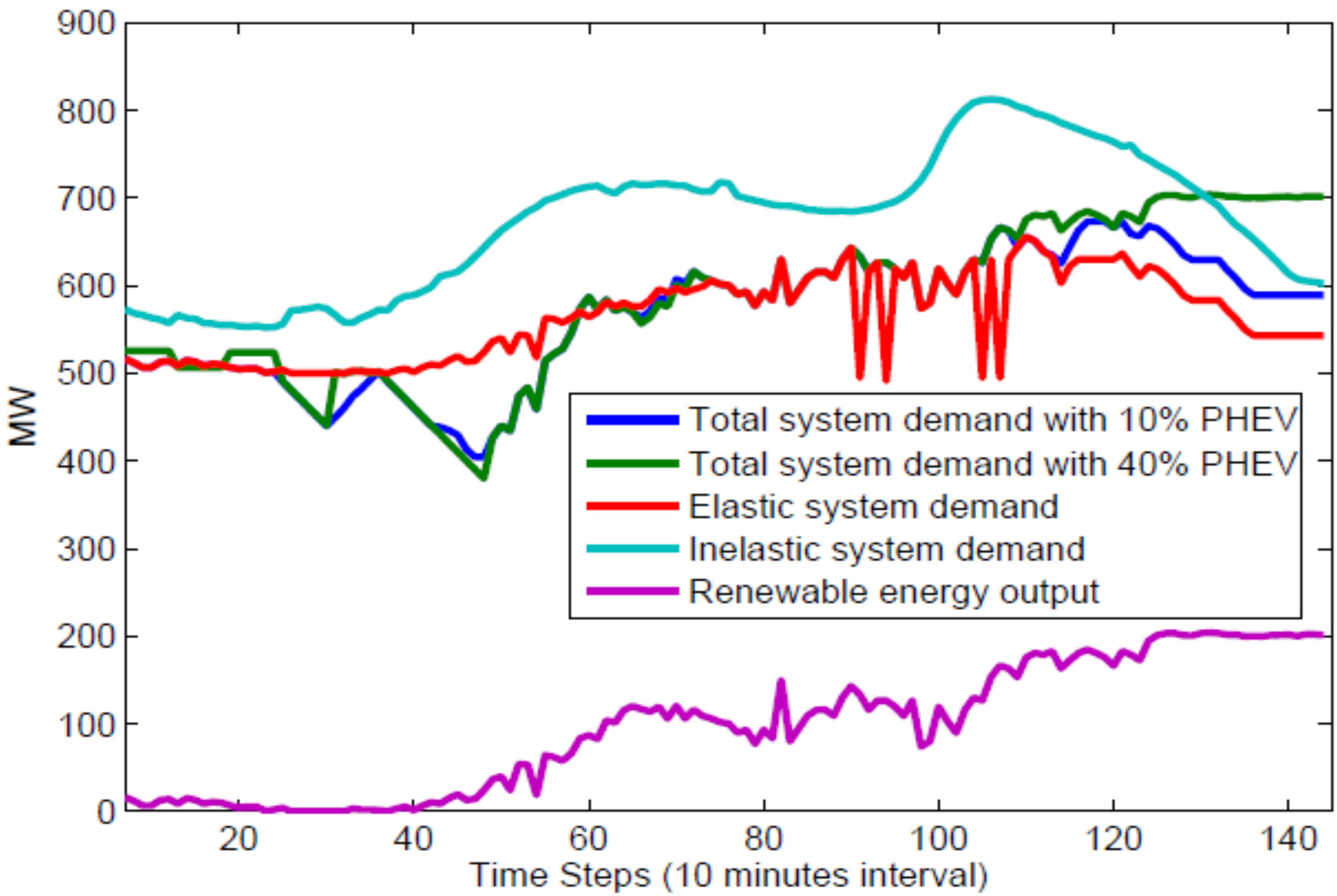


- Interchange supply / demand mode by time-varying prices

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

Huge opportunity which will probably not be explored

- Daunting roadblocks:
- The fastest time scale –make it as localized as possible but use lots of data for model verification
- Can it be done to protect privacy of data that should not be exchanged?
- Can it be done at provable performance?

  -secure reliable state estimation

  -off-line data processing for feed-forward applications (scheduling for the worst case; parallel processing of likely failures)

  -management of multi-area

  -limits to using big data

Looking ahead- Framework for integrating combination of technologies at value

- Value is a system-dependent concept (time over which decision is made; spatial; contextual)
- Cannot apply capacity-based thinking; cannot apply short-run marginal cost thinking
- Reconciling economies of scope and economies of scale
- Value of flexibility (JIT,JIP, JIC)
- Hardware, information, decision-making software; distributed, coordinated –all have their place and value

Perhaps the hardest challenge ahead…

- Once possible new CPS paradigms are shown using proof-of-concept simulations

  -develop user-friendly simulators to educate potential users, technology developers and regulators

  -methods for incentivizing deployment at value

  -cyber plays the key role!