Carnegie Mellon

Electric Energy Systems Group

Electrical & Computer ENGINEERING

A New Unifying Modeling for Scalable Simulation-based Test Beds of Future Electric Energy Systems—Smart Grid in a Room Simulator (SGRS) at CMU

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JST-NSF-DFG Workshop on Distributed Energy Management Systems

NSF, Arlington VA

April 20-23, 2015

Acknowledgments

Funding– **NSF awards:** (1) # 0428404 ITR - \(ASE+NHS\) -\ (dmc+int\): Toward a Multi-Layered Architecture for Reliable and Secure Large-Scale Networks: The Case of an Electric Power Grid,2005-2009 (Ilic); (2) #0343760: Educating 21st Century Power Engineers 2004-2007; (3) NSF #0931978 (Negi, Ilic) CPS:MEDIUM:A Computing Framework for Distributed Decision Making to Ensure Robustness of Complex Man-Made Network Systems: The Case of the Electric Power Networks (2009-2014); **PSERC Projects** (S-37: Toward a systematic deployment of synchrophasors and their utilization for Improving performance of Future Electric Energy Systems**;** S-55: Toward standards for dynamics in electric energy systems;M-31: Markets for Ancillary Services in the Presence of Stochastic Resources); **Several industry projects** (ABB, Converteam, Bosch, IBM,Nexans)

- Concepts based on collaborative work at Carnegie Mellon University's Electric Energy Systems Group (EESG), Ilic team http://www.eesg.ece.cmu.edu/.

The system works today, but…-some very real problems needing solutions

- 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

Need for a new paradigm

- Today's industry approach– the worst case approach, inefficient and does not rely on on-line automation and regulation other than energy feed-forward economic dispatch
- Emphasis on large-scale time-domain system simulations for transient stability, voltage, collapse, power flow feasibility, etc
- Primary control is constant gain tuned assuming no dynamic interactions with the rest of the system
- Existing and emerging system-level unacceptable interactions; no incentives for ``smarts" of modules

Fundamental challenge

- Modeling/operating new paradigm; education to support evolution from today's approaches
- The key role of smarts in implementing sustainable socio-ecological energy systems
- New physics-based modeling
- Emerging cyber paradigms

  --for micro-grids

  --for bulk- power grids

  --for hybrid power grids

  --assumptions made and their implications

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?

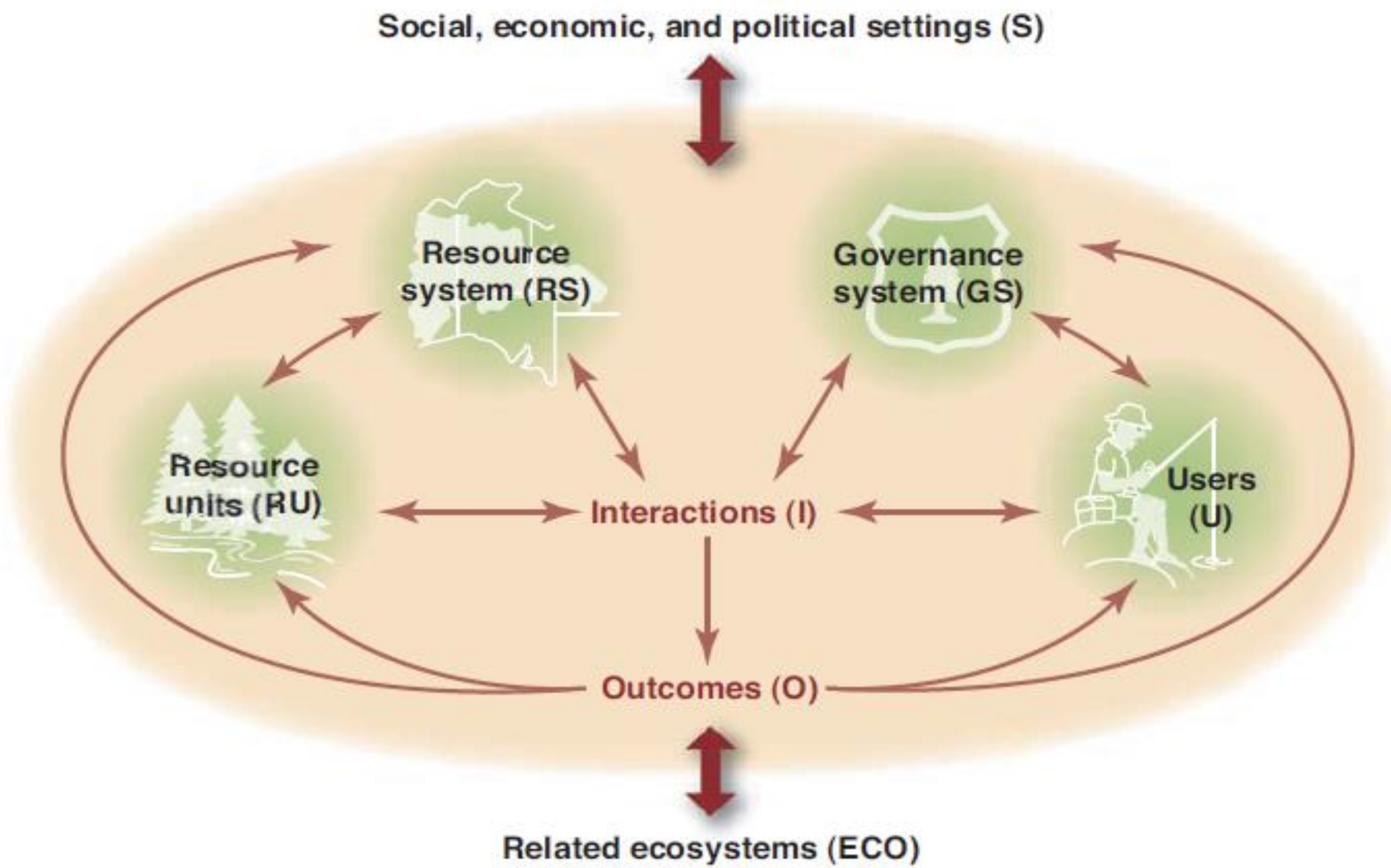

Fig. 1. The core subsystems in a framework for analyzing social-ecological systems.

"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

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

Fundamental observation--Cyber architectures trailing behind; one size doesn't fit all but possible to have a unifying framework with **common design principles**

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Azores Island—Flores

Figure 1: Satellite image of Flores Island.

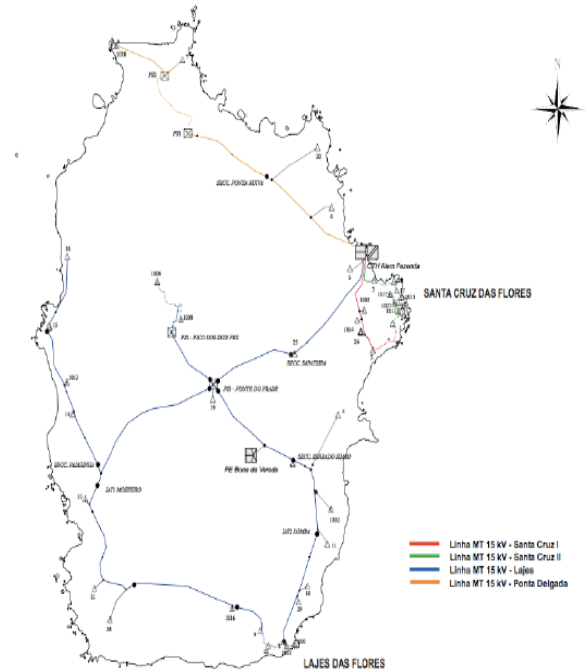
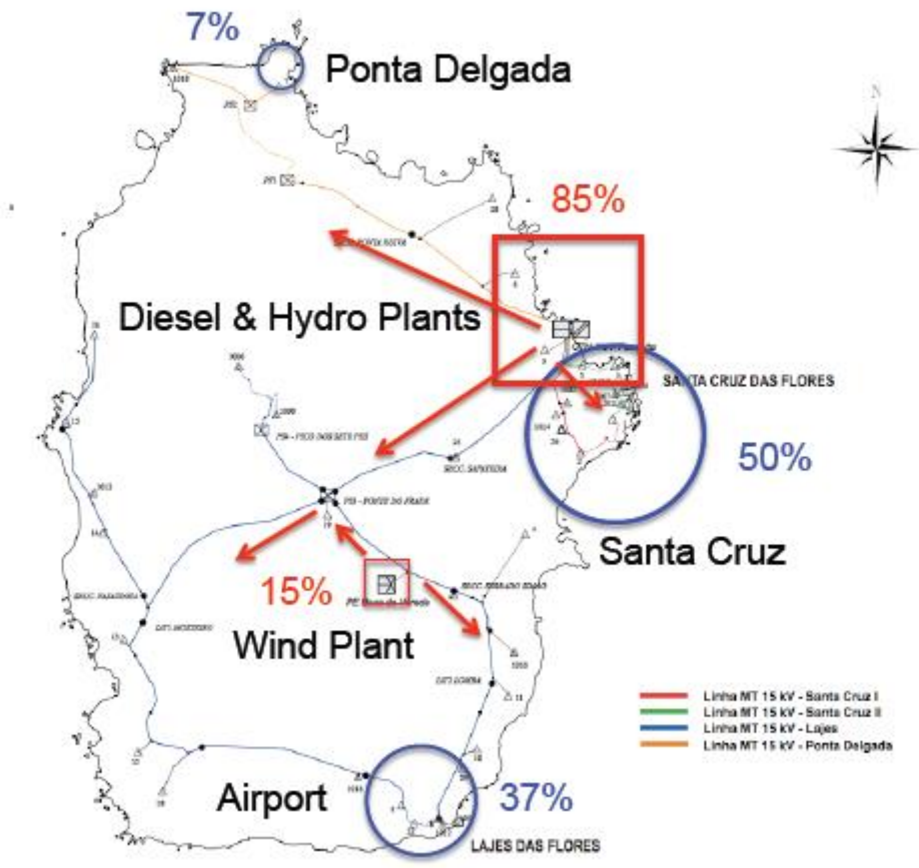
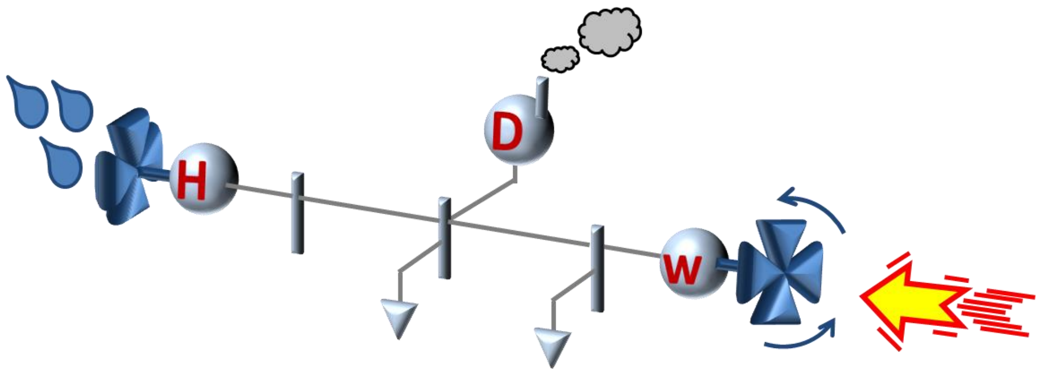


Figure 2: Electrical Network of Flores Island.

Motivating example---From old to new paradigm—Flores Island Power System, Portugal [3]



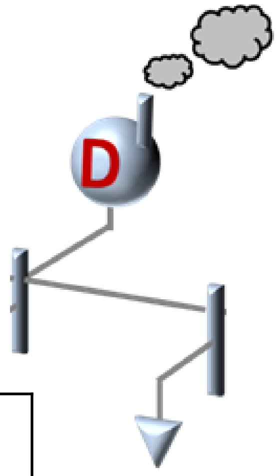
Controllable components—today's operations (very little dynamic control, sensing)



H – Hydro
D – Diesel
W – Wind

*Sketch by Milos Cvetkovic

Two Bus Equivalent of the Flores Island Power System



State	Equilibrium
$e_q'[pu]$	0.9797
$\delta[rad]$	0.0173
$\omega[pu]$	1
$v_r[pu]$	0.8527
$e_{fd}[pu]$	0.7482
$v_f[pu]$	0
$P_m[pu]$	0.01
$a[pu]$	0

Generator	Diesel
$x_d[pu]$	8.15
$x_q[pu]$	8.15
$x_d'[pu]$	0.5917
$x_q'[pu]$	0.5917
$T_{q0}'[s]$	2.35
$T_{d0}'[s]$	2.35
$J[s]$	2.26
$D[pu]$	0.005

Transmission line	From Diesel to Load bus
$R[pu]$	0.3071
$L[pu]$	0.1695

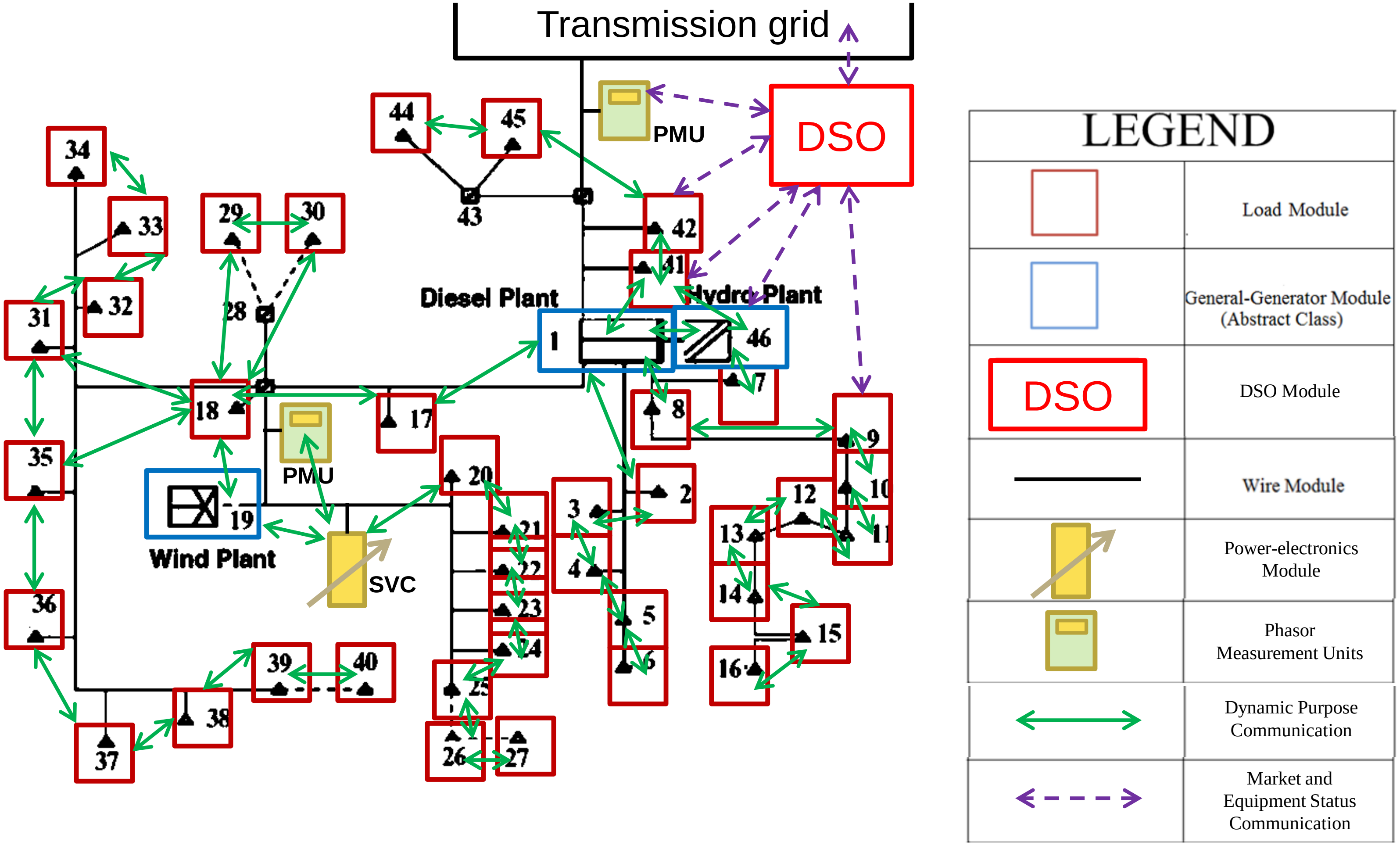
Base values
$S_b = 10MVA$
$V_b = 15KV$

AVR	Diesel
$K_A[pu]$	400
$T_A[s]$	0.02
$K_E[pu]$	1.3
$T_E[s]$	1
$S_E[pu]$	0.1667
$K_F[pu]$	0.03
$T_F[s]$	1

Governor	Diesel
$k_t[pu]$	40
$T_g[s]$	0.6
$r[pu]$	1/0.03
$T_t[s]$	0.2

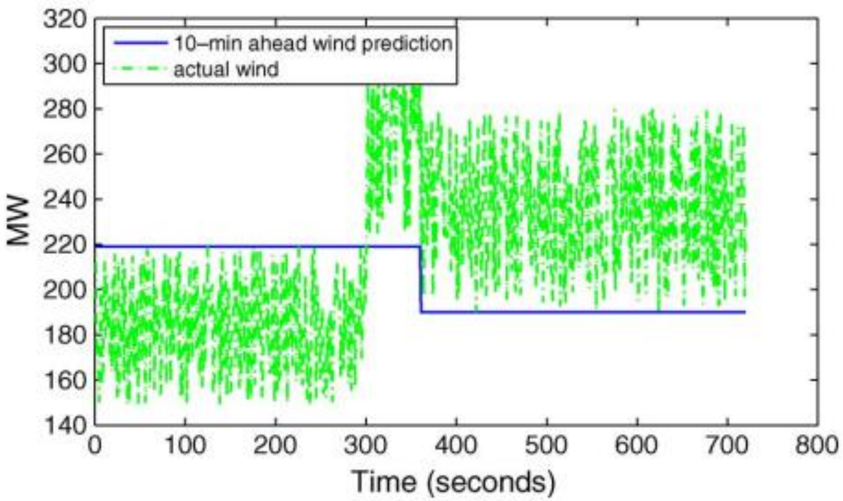
Base values $S_b = 10MVA, V_b = 0.4KV$

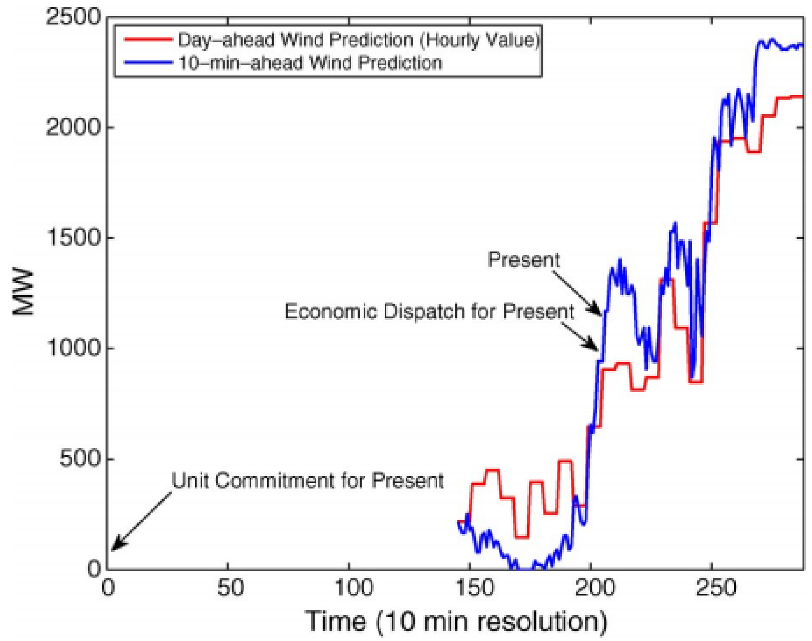
Information exchange in the case of Flores---new (lots of dynamic control and sensing)



Wind power disturbance – multiple time scales

- Observe the non-zero mean deviation from prediction ⇨ disequilibria conditions





$$P_{Gw}(t) = \hat{P}_{Gw}[H] + \Delta_{Gw_H}(t)$$

$$P_{Gw}(t) = \hat{P}_{Gw}[k] + \Delta_{Gw_k}(t)$$

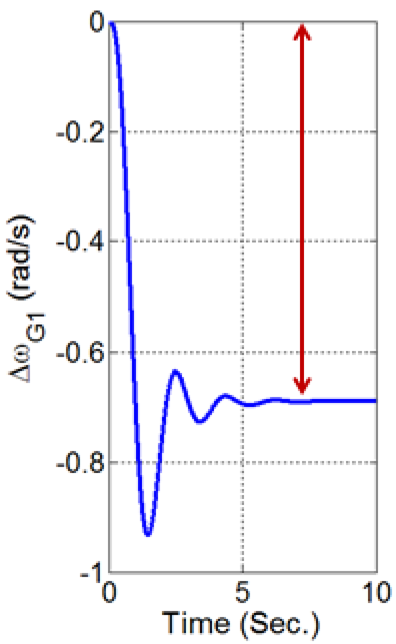
$$\|\Delta_{Gw_H}(t)| \gg \|\Delta_{Gw_k}(t)\|$$

$$\left\|\hat{P}_{Gw}[k]\right\| \gg \|\Delta_{Gw_k}(t)\|.$$

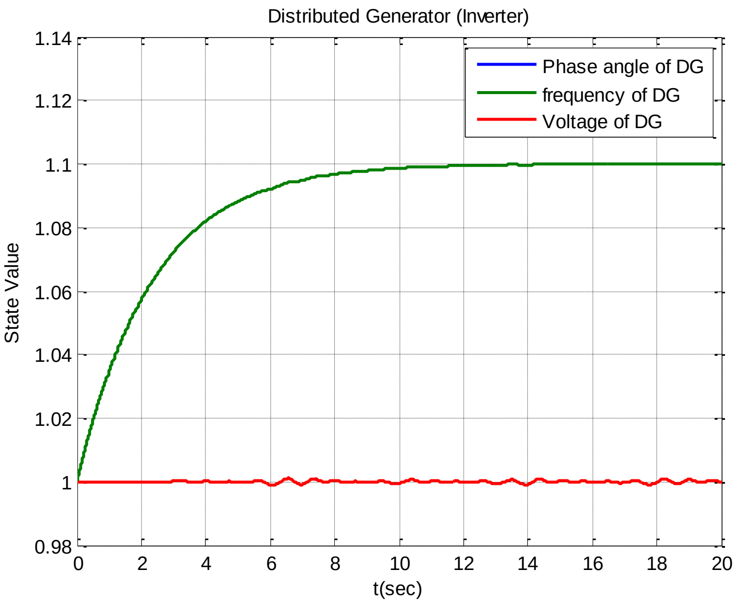
Xie, L., Carvalho, P. M., Ferreira, L. A., Liu, J., Krogh, B. H., Popli, N., & Ilic, M. D. (2011). Wind integration in power systems: Operational challenges and possible solutions. *Proceedings of the IEEE*, *99*(1), 214-232.

Fundamental effect of non-zero mean disturbance —new operating problems

- Synchronous machine with non zero mean disturbance in real power load
  - Structural singularity [2]



- Wind power plant with power electronics connected to constant impedance load [3]



[2]Q. Liu. Wide-Area Coordination for Frequency Control in Complex Power Systems. Ph.D. Thesis, CMU, Aug 2013.
[3] X. Miao, M. Ilic. EESG working paper, 2015

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
- 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

Time-space complexity/structure 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

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

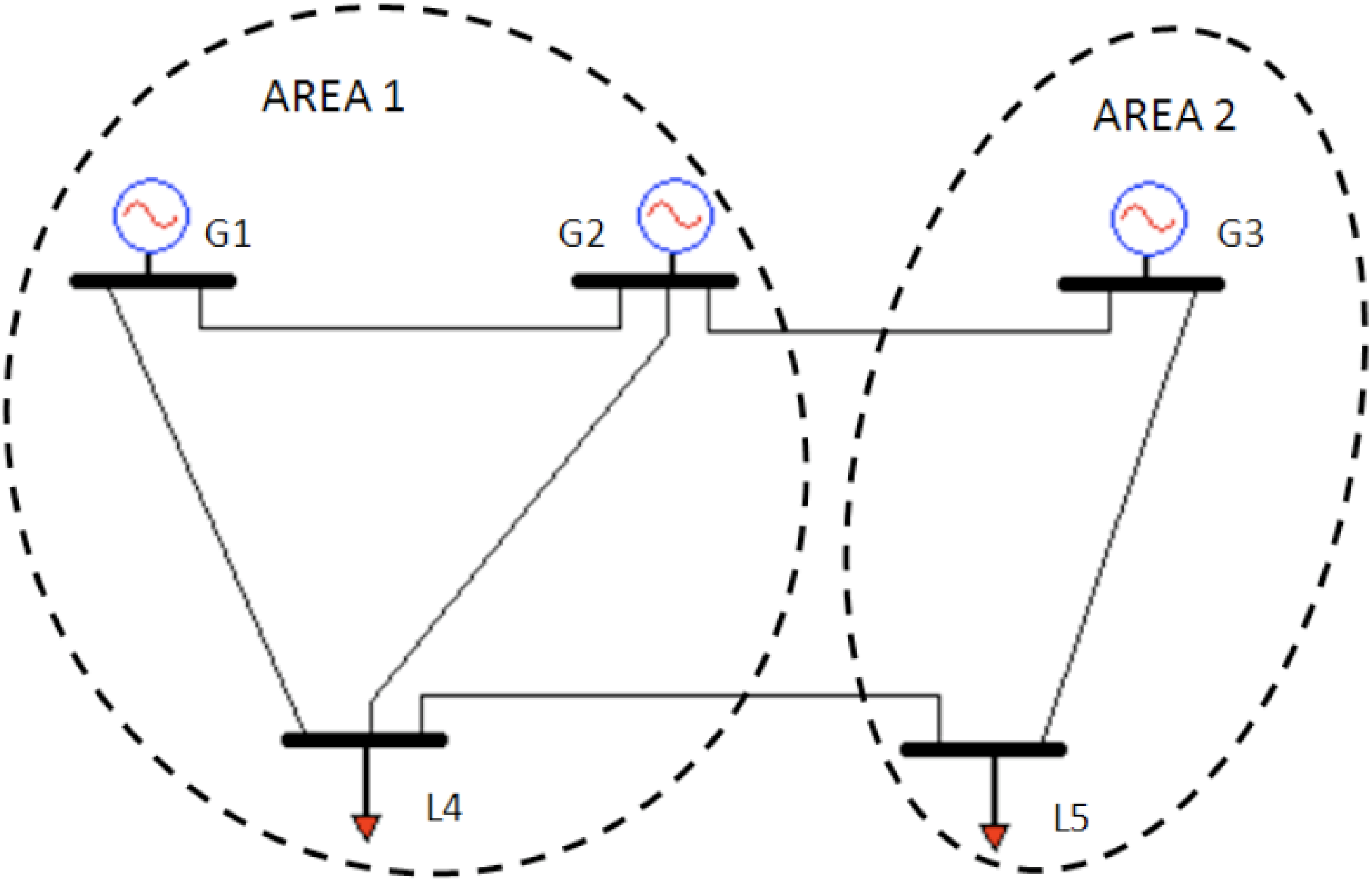
  -DyMonDS for internalizing temporal uncertainties and risks at the resource and user level; interactive information exchange to support distributed optimization

  -perform static nonlinear optimization to account for nonlinear network constraints

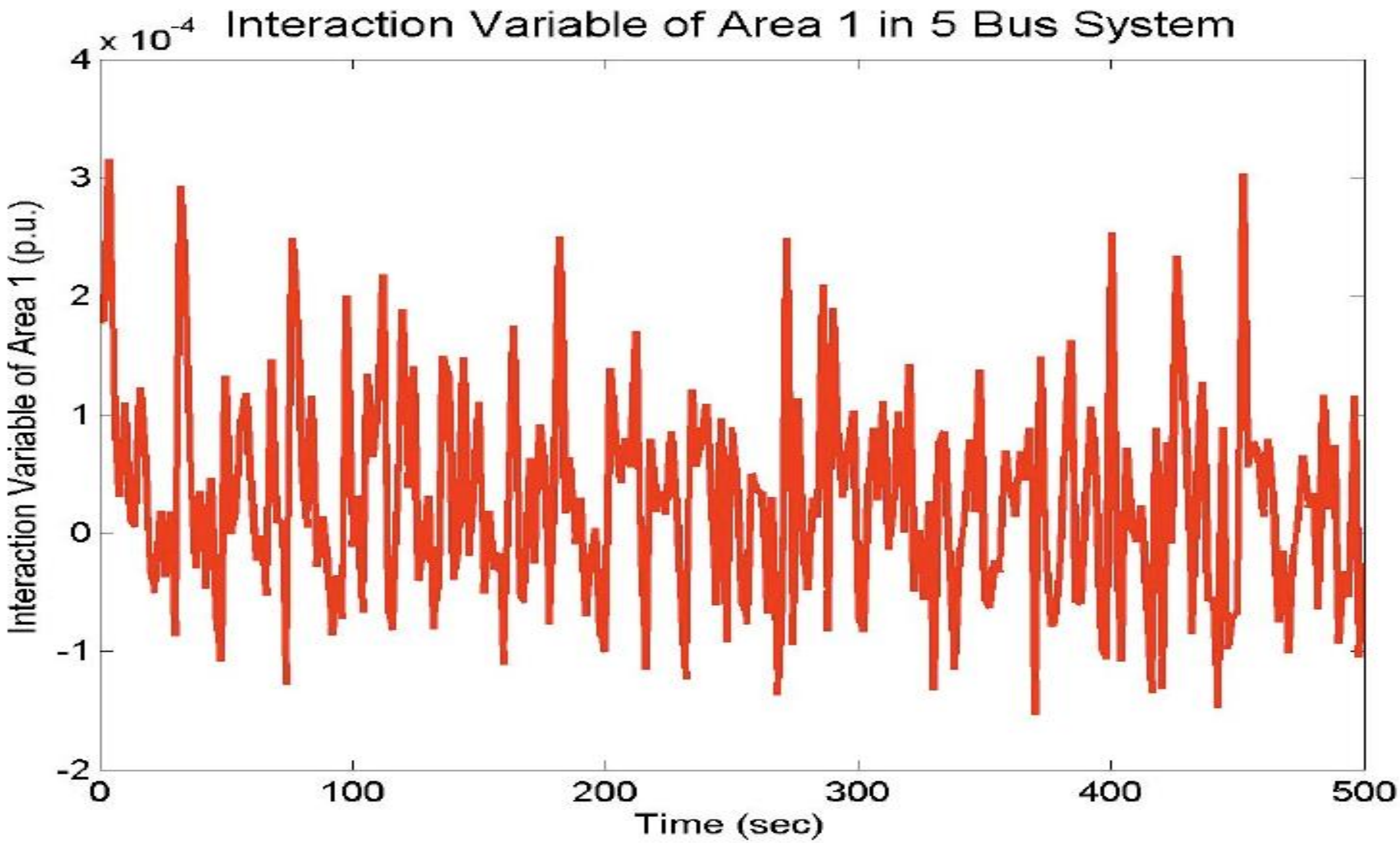
  -enables corrective actions
- Simulation-based proof of concept for low-cost green electric energy systems in the Azores Islands

Vast temporal and spatial physical interactions

Interaction Variable Simulation for Real Power Problem in 5 Bus System



Vast temporal and spatial inter-dependencies –may want to either cancel them (decentralized stabilization) or cooperate (for efficiency)



Aligning physics and modeling to prove existence of IntV

- 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**

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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 $A_{a,k}$

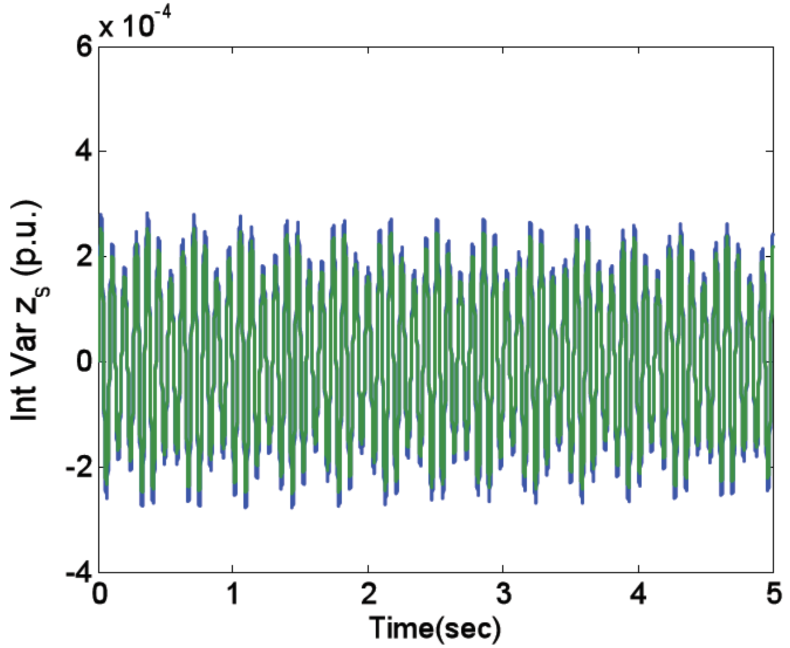
- Dynamic model

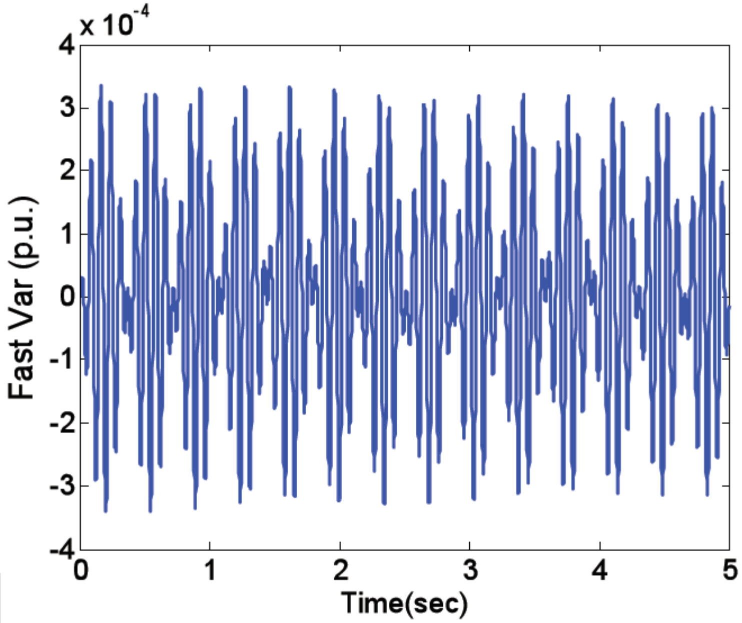
$$\dot{z}_{a,k} = T_{a,k} \sum_{h=1}^{N_a} A_{a,kh} x_{a,h} + T_{a,k} B_{a,k} u_{a,k},$$

- 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**

Strongly coupled subsystems

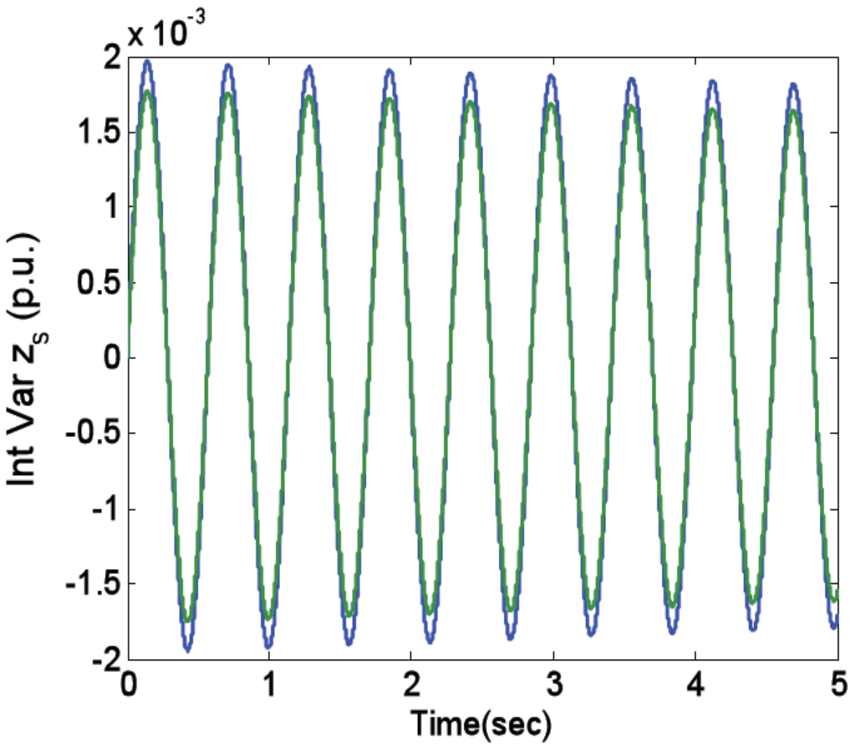
- Not possible to make the key hierarchical system assumption that fast response is always localized; dead-end to classical LSS
- Fast control must account for system-wide interactions

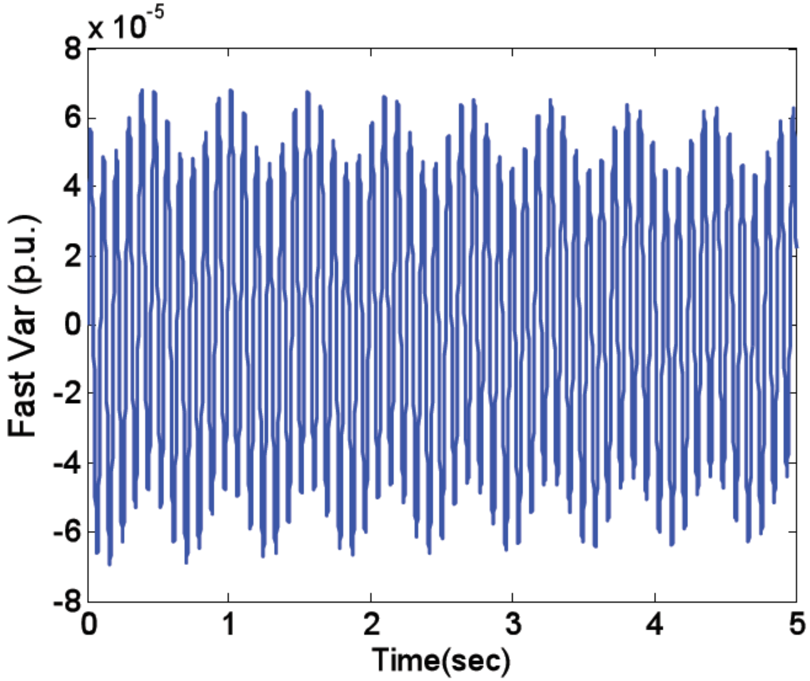




Weakly coupled subsystems

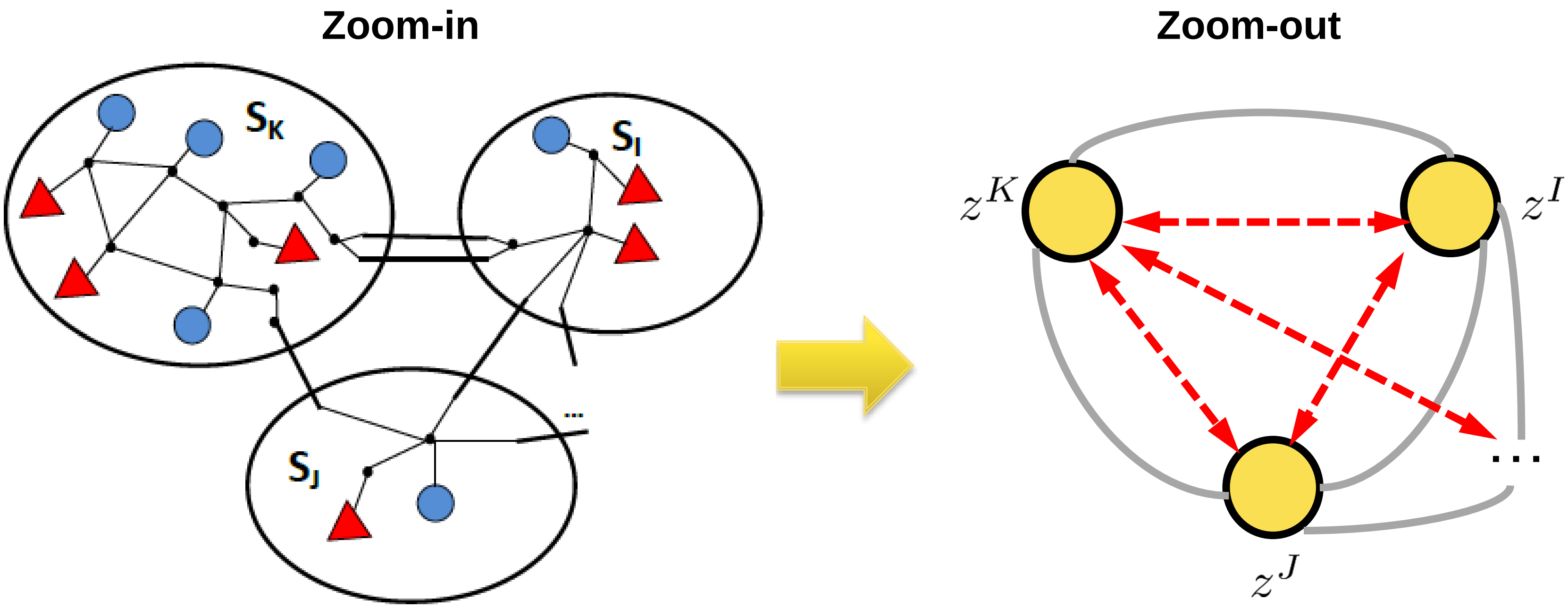
Interaction Variables of S1 and S2





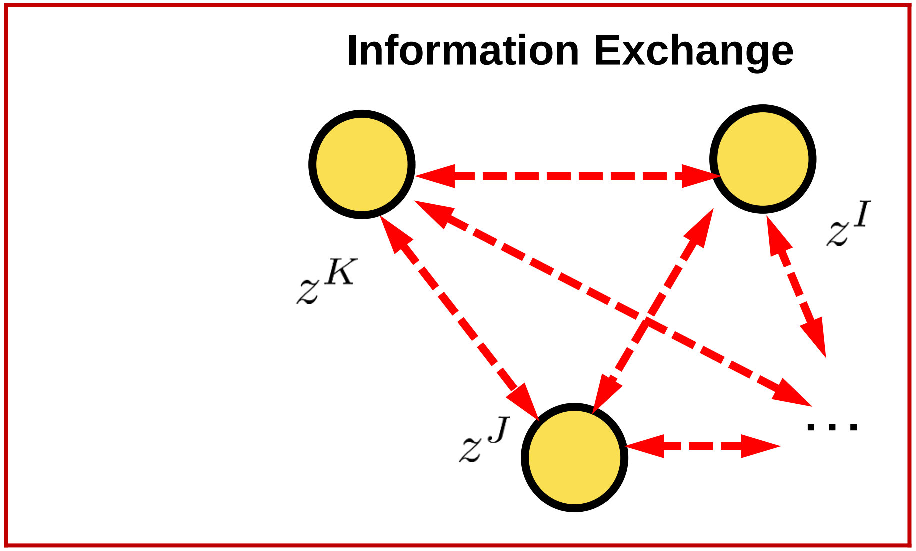
IntV-based approach to coordinated dynamics

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



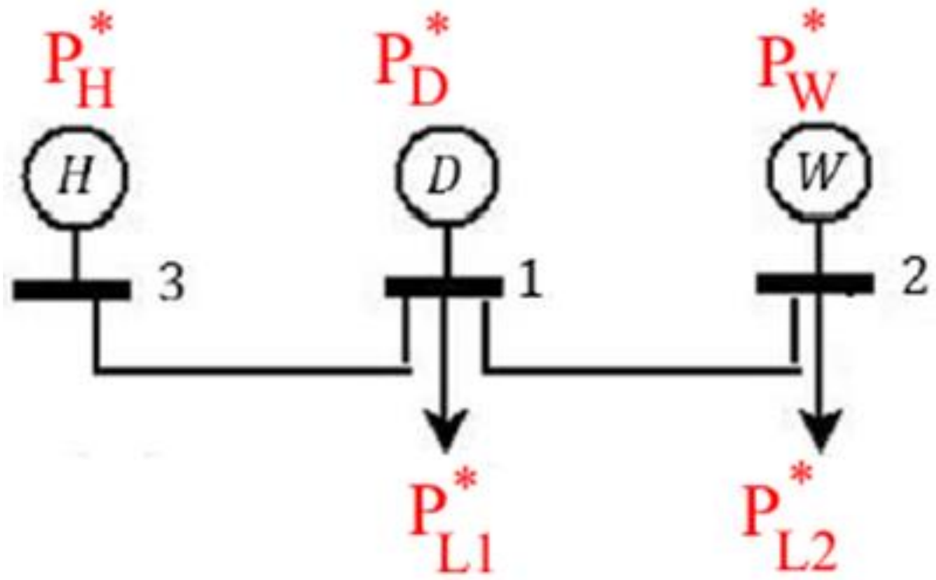
IntV-based minimal coordination

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



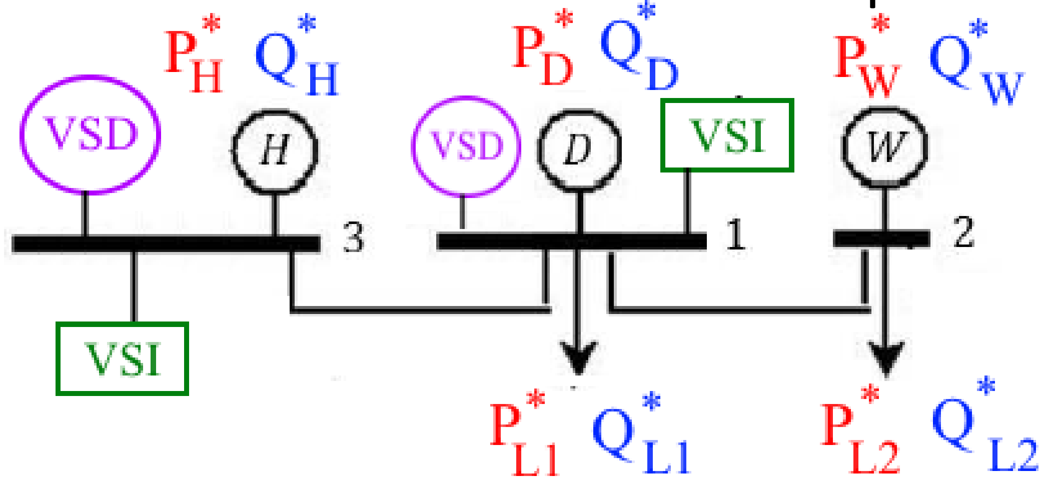
Flores Island – Market

- Based on prices, market computes active power set points P* from each component



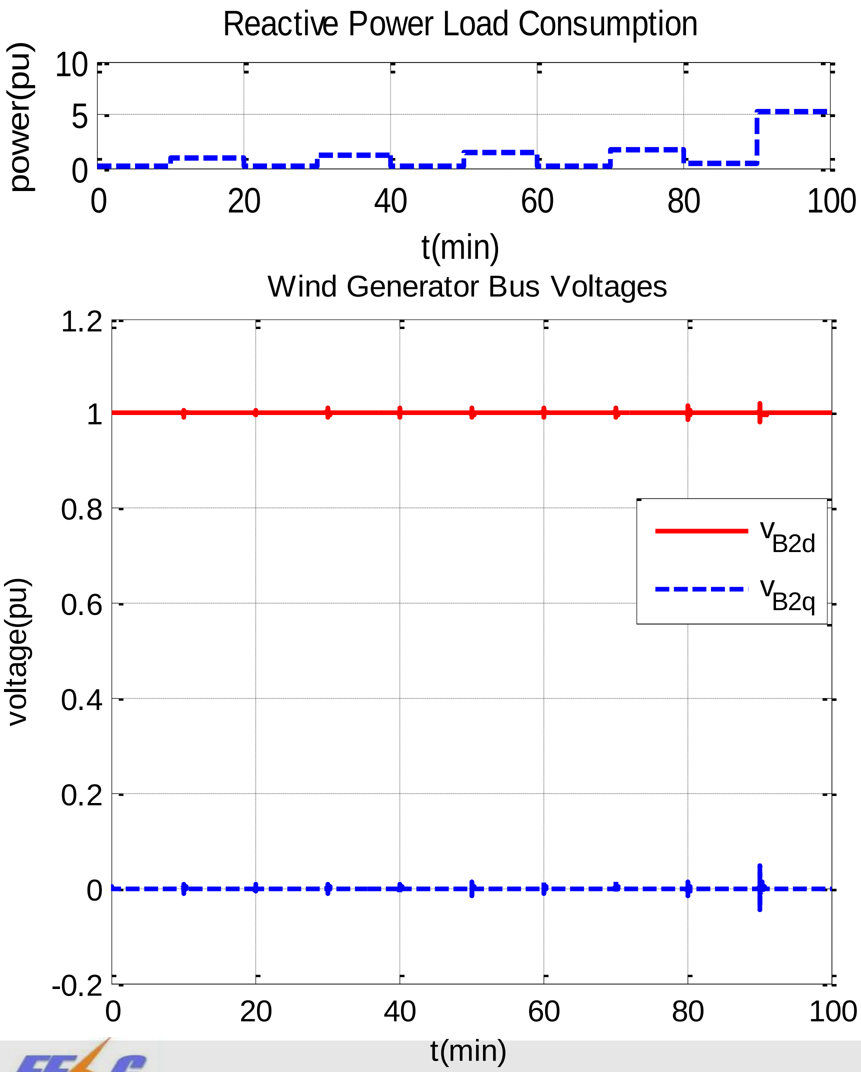
Flores Island – Nonlinear Interaction Dynamics

- Since currently the market does not specify reactive power set points Q*, data for Q* is randomly created
- Place a voltage source inverter and the variable speed drive on the hydro and diesel generator buses
- Control the sum of the power out of the hydro and diesel generators to match the active and reactive power set points

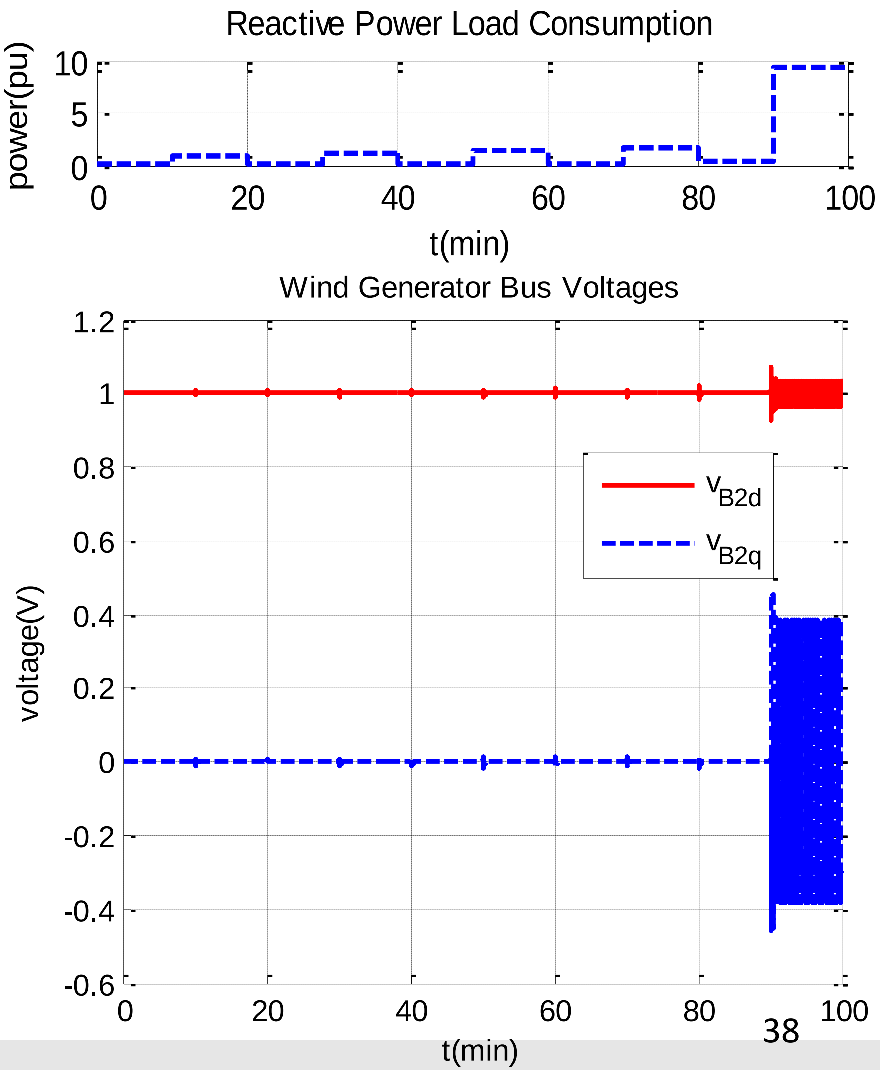


Simulation Results – Combining Dynamics and ALM

Stable Case:



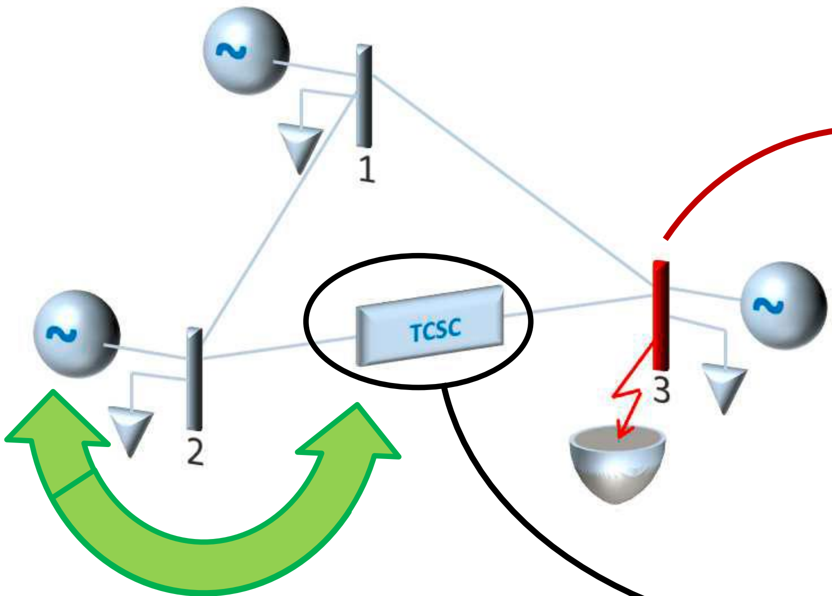
Unstable Case:

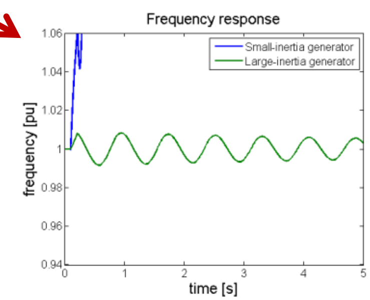


Transient Stabilization of Interactions Using FACTS

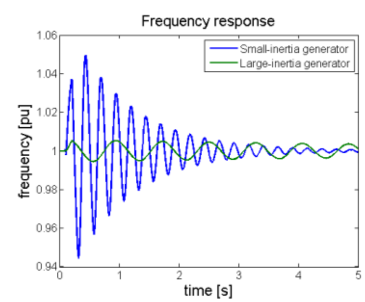
Transient stability problem

- ***Nonlinear dynamics***
- ***Multiple time scales***
- ***Large regions***





Unstable



Stable

Interactions are captured using an energy-based model

- ***Accumulated energy as a measure of stability***
- ***Managing energy to ensure stability***

<u>Cooperative</u> power electronics (FACTS) control

- ***Fast thyristor switching***
- ***Flow control***

Common Modeling Approach for FACTS Control

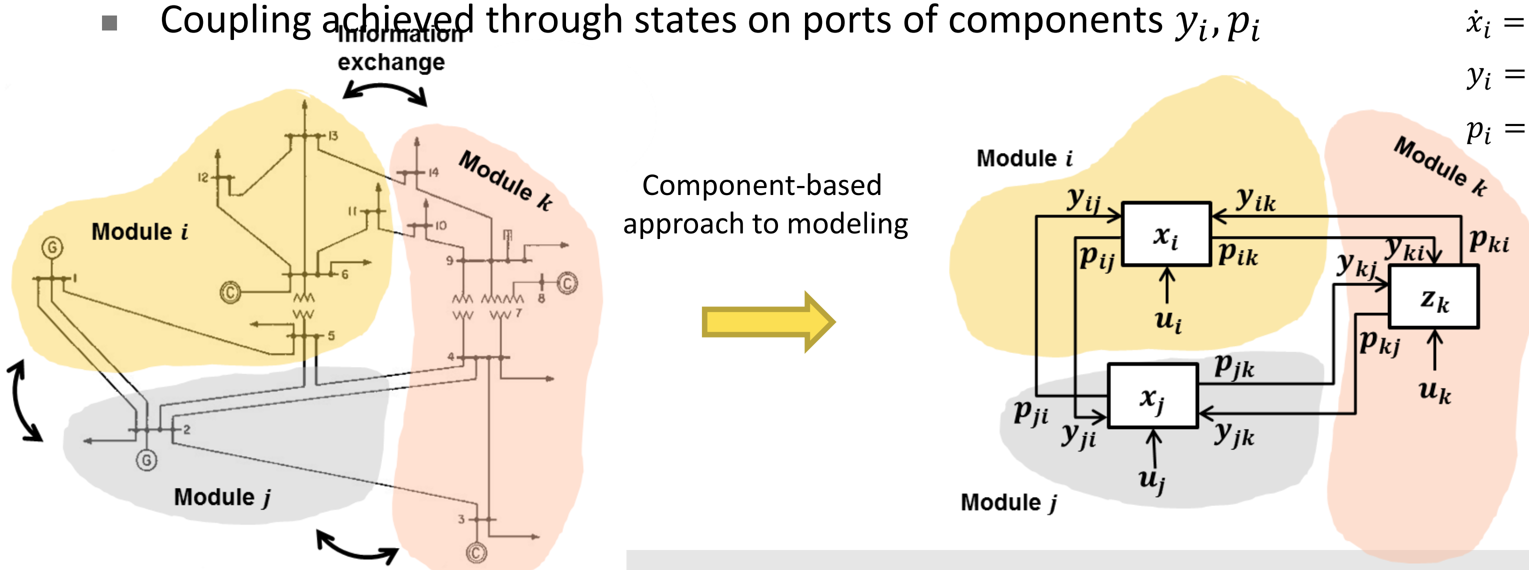
- Create a simplified power system model
  - Control logic is case dependent
  - Loaded as test case for transients simulator
- Create a structure preserving system model by combining dynamic models of individual components
  - Coupling achieved through states on ports of components y_i, p_i

Module description

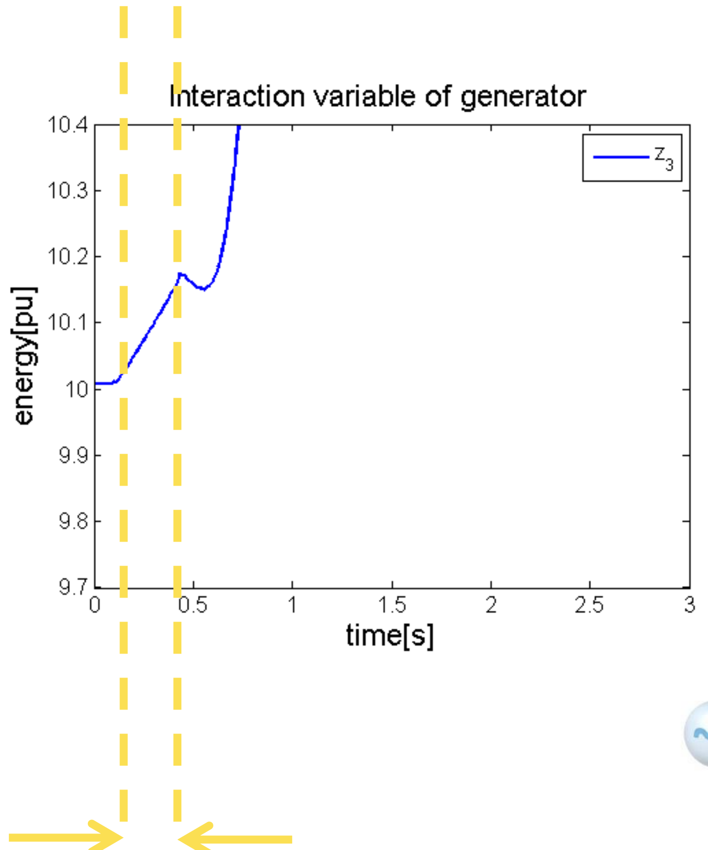
$$\dot{x}_i = f_i(x_i, y_i, u_i, d_i)$$

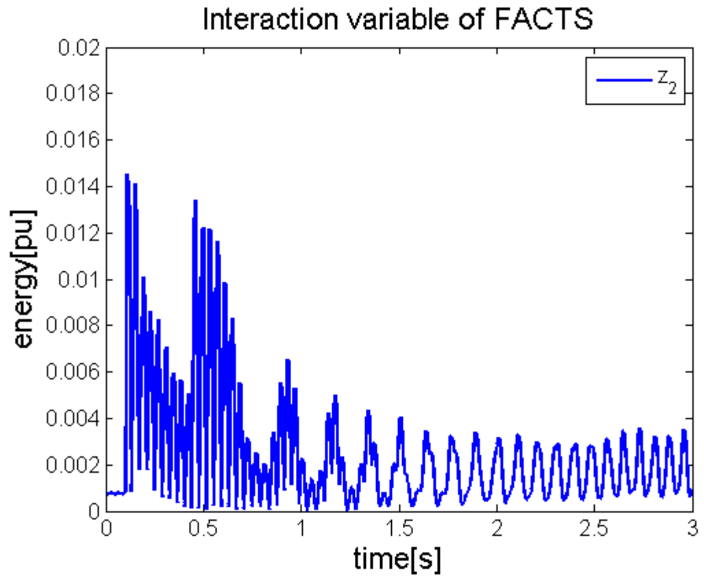
$$y_i = [y_{ij}(x_j) \quad y_{ik}(x_k)]$$

$$p_i = [p_{ij}(x_i) \quad p_{ik}(x_i)]$$

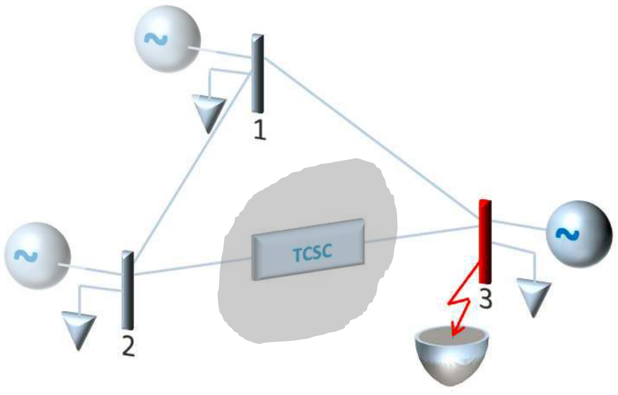


Response of uncontrolled system— “harmonic instability”

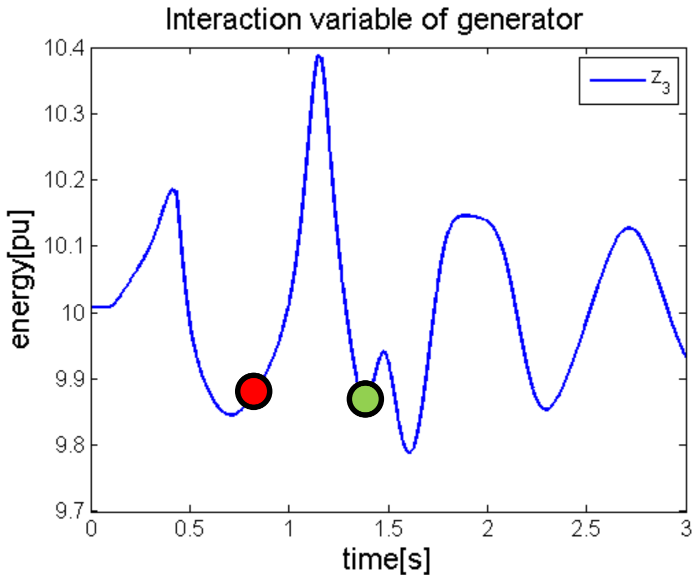


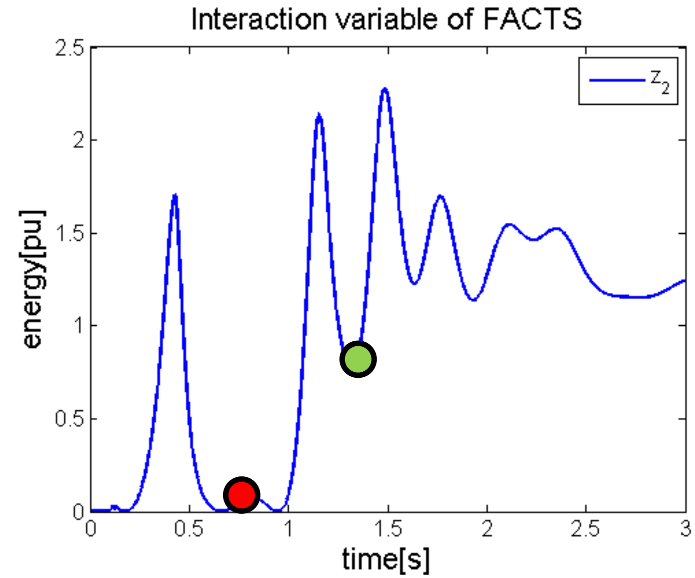


Short circuit at bus 3
in duration of 0.35 sec



Controlled System Response



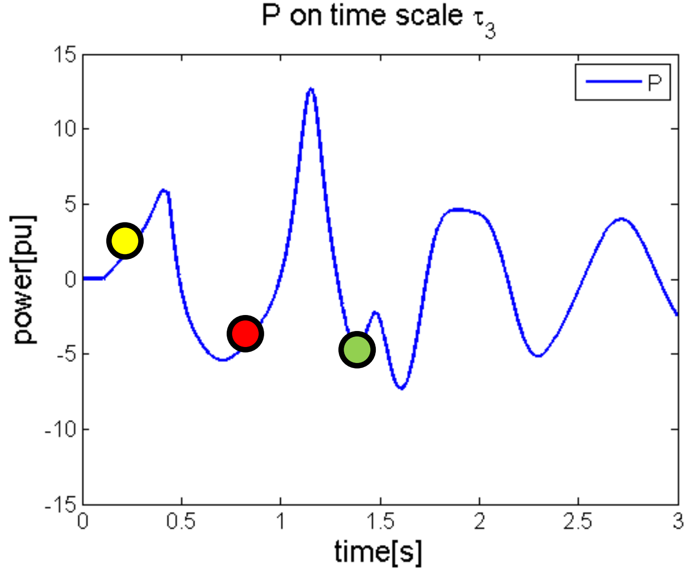


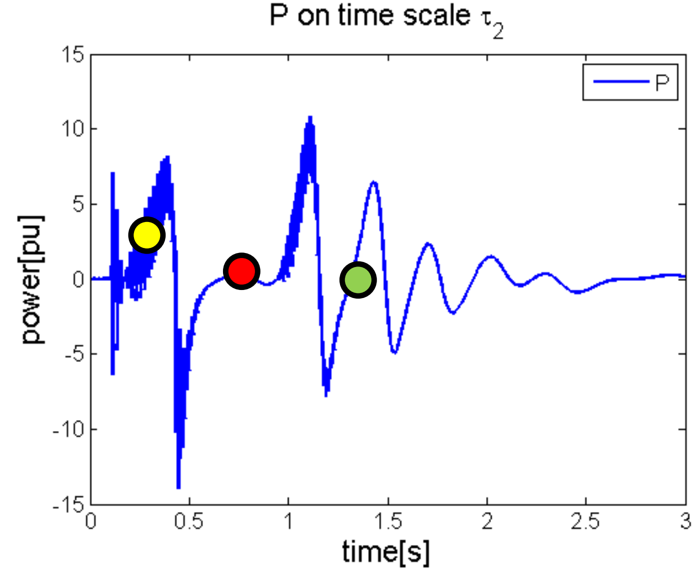
$$P_{\tau_3} = \frac{1}{\tau_3} \int_{\tau_2} P_{\tau_2} dt$$

$z_2 = 0$

FACTS energy has reached zero

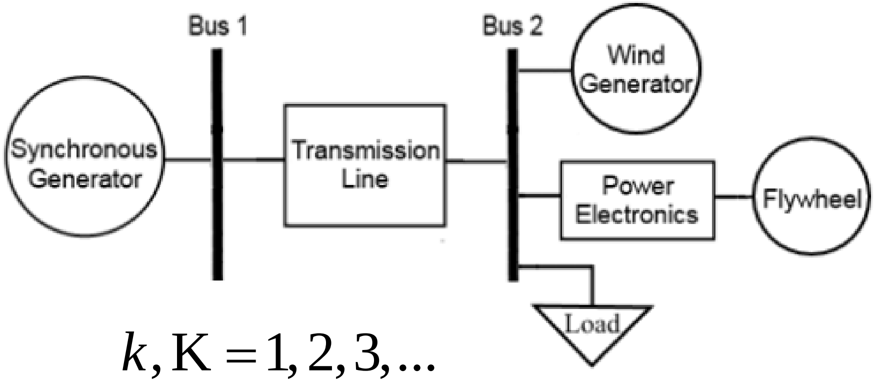
States converge to a different equilibrium





Multi-temporal dynamic model of controllable load (DER)—stand-alone module level

- DER dynamics replaces static load and is modeled as any other dynamic component with non zero exogenous disturbance



$$\dot{x}_i(t) = f_i\left(x_i(t), x_j(t), u_i(t), m_i(t)\right)$$

$$x_i(0) = x_{i0}$$

$$m_i(t) = M_i[K \cdot T_M] + M_i[k \cdot T_s] + \Delta m_i(t)$$

where $m_i(t)$ – Exogenous input

$x_i(t)$ – State variable of Module i

$x_j(t)$ – State variable of Module j, $j \in C_i$

$k, \mathrm{K} = 1, 2, 3, \ldots$

$T_M = 10\,\text{min}, 1\text{ hour}, 24\text{ hour}$

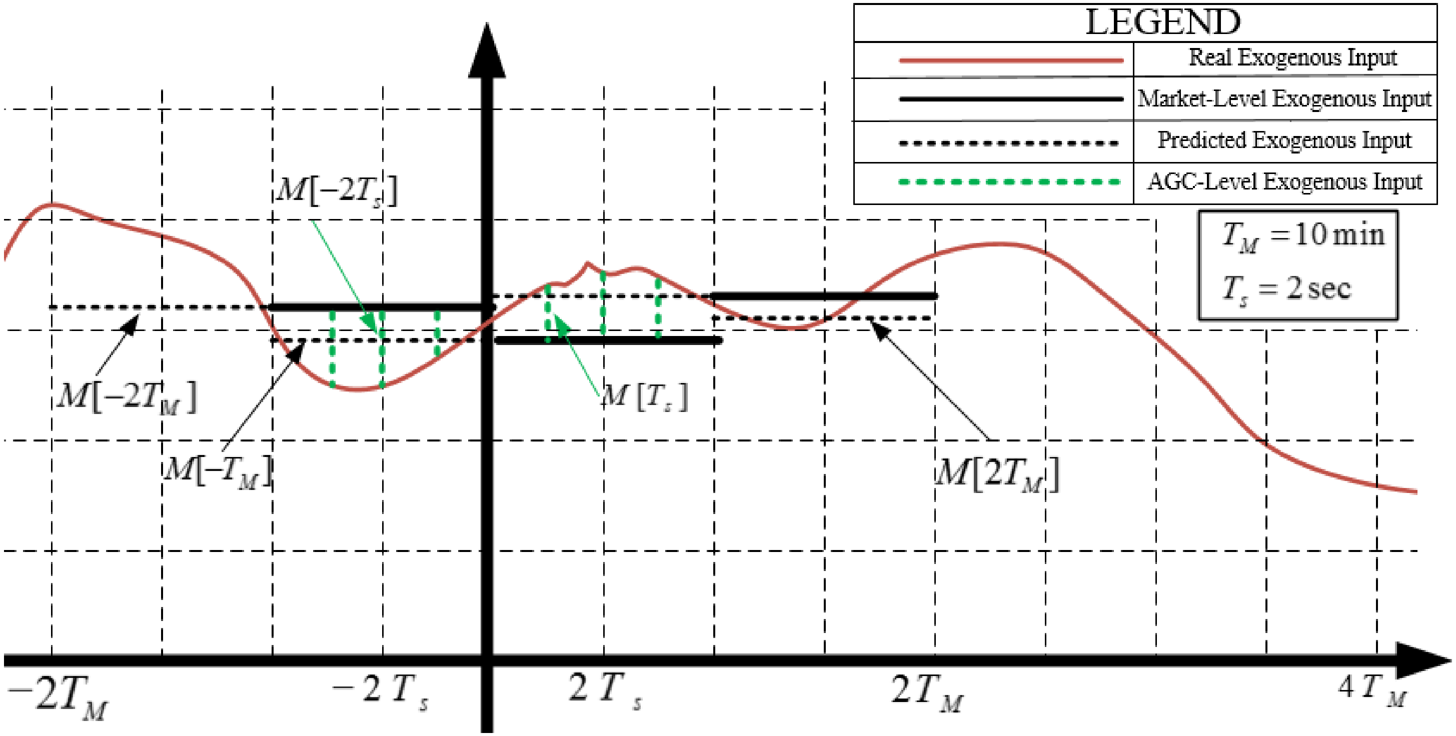
$T_s = 1 - 60\,\text{sec}$

- Responsive load (for example: Smart building) can have:

$$u_i = \boxed{u_i(t)} + \boxed{u_i^{ref}[k \cdot T_s]} + \boxed{u_i^{ref}[k \cdot T_M]}$$

Local AGC Market

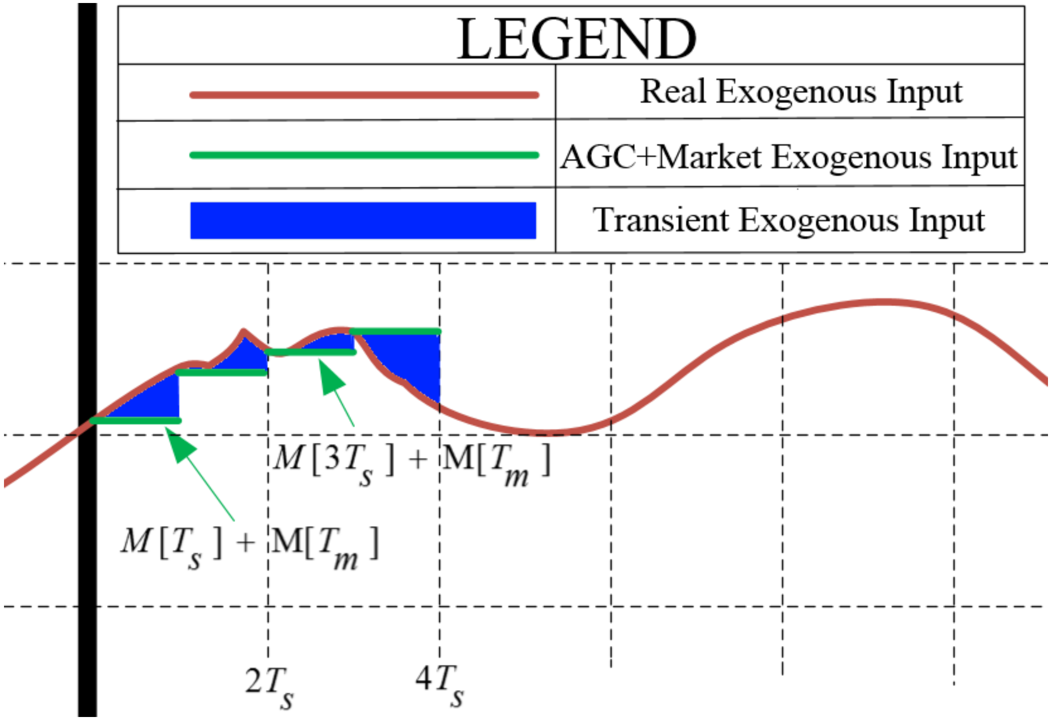
Multi-temporal exogenous input – Zoom Out



$$m_i(t) = M_i[K \cdot T_M] + M_i[k \cdot T_s] + \Delta m_i(t)$$

Real Exogenous Input — Market-Level Exogenous Input — AGC-Level Exogenous Input — Transient Exogenous Input

Multi-temporal exogenous input – Zoom In



$$m_i(t) = M_i[K \cdot T_M] + M_i[k \cdot T_s] + \Delta m_i(t)$$

Real Exogenous Input

Market-Level Exogenous Input

AGC-Level Exogenous Input

Transient Exogenous Input

Generalized multi-temporal family of interacting models – module level

Electromagnetic (EM) phenomena	Electro-mechanical (EMEch) phenomena	Quasi-stationary (QS) regulation	QS short-term	QS long(er)-term
Time-varying phasors (EM)	Time-varying phasors (EMech)	$P[kT_s], Q[kT_s]$, $V[kT_s]$ driven by $M[kT_s]$; controlled by $u[kT_s]$	$P[KT_t], Q[KT_t]$, $V[KT_t]$ driven by $M[KT_t]$ and controlled by $u[KT_t]$	New equipment/topology driven by long-term predictions

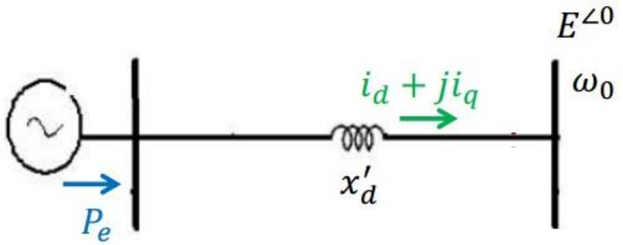
Multi-layered interactive models for interconnected system (unifying transformed state space)

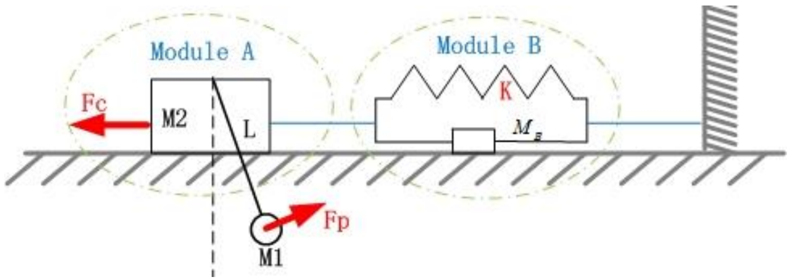
- Standard state space of interconnected system

$$\dot{\bar{\bar{X}}}_A = f_A\left(\bar{\bar{X}}_A, Z_A, P_A, u_A\right)$$

Interaction level model for coordination

$$\dot{Z}_A = f_{ZA}\left(\bar{\bar{X}}_A, Z_A, P_B\right)$$
$$\dot{P}_A = f_{PA}\left(\bar{\bar{X}}_A, P_A, \dot{P}_B\right)$$
$$\dot{Z}_B = f_{ZB}\left(Z_B, P_A, u_B\right)$$
$$\dot{P}_B = f_{PB}\left(P_B, \dot{P}_A\right)$$

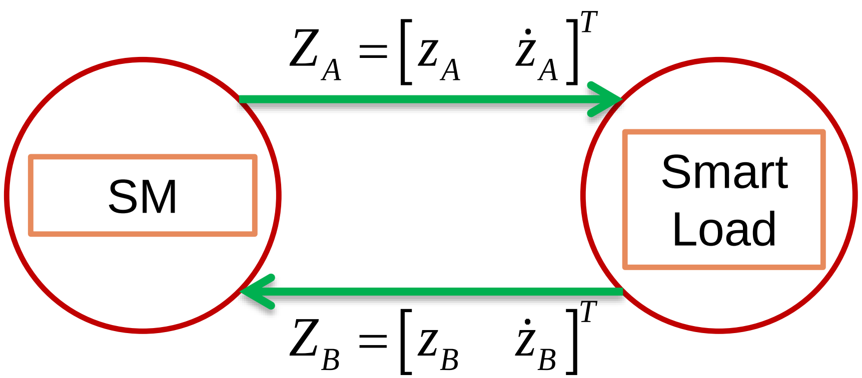




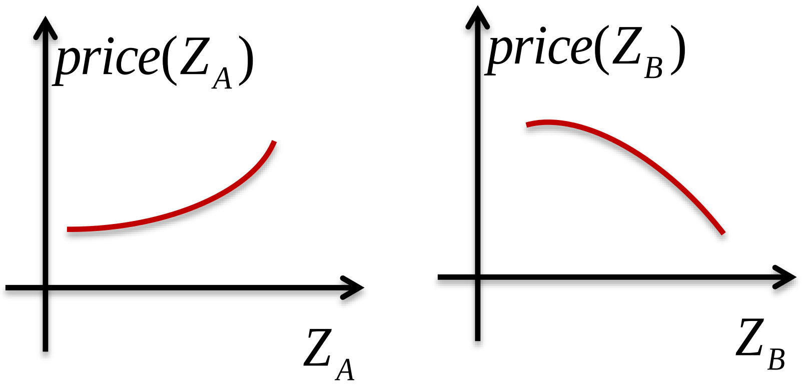
- Less assumption and communication are needed;
- System dynamics are separated into multi-layer system: internal layer and interaction layer;
- Based on above frame work, different control strategy can be used and designed: competitive or cooperative control

Required information exchange for interconnected system

- To ensure reliability (stability, feasibility)
  - Must be exchanged interactively. They represents the total incremental energy & its rate of change; In steady state, decoupled assumption will be ***P & Q***
  - Ranges (convex function) instead of points exchanged (DyMonDS)



- For distributed interactive optimization
  - System-level optimization is the problem of "clearing" the distributed bids according to system cost performance [P, Q info processing requires AC OPF instead of DC OPF]



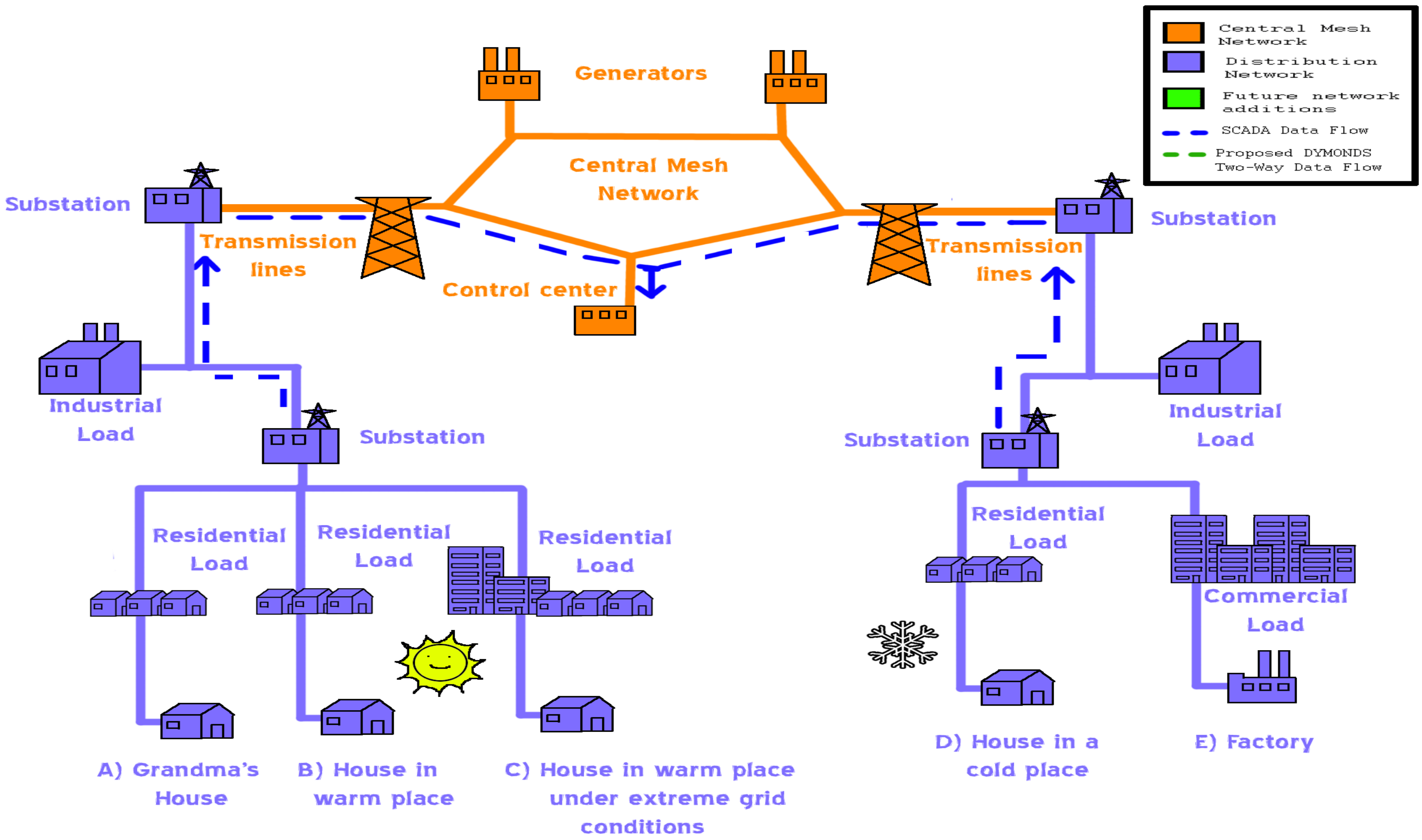
Smart grid ---
multi-layered interactive dynamical system

- Requires new modelling approach
- Key departures from the conventional power systems modeling
  - system is *never* at an equilibrium
  - all components are dynamic (spatially and temporally); often actively controlled
  - 60Hz component may not be the dominant periodic signal
  - system dynamics determined by both internal (modular) actions and modular interactions
- Groups of components (module) represented in standard state space form

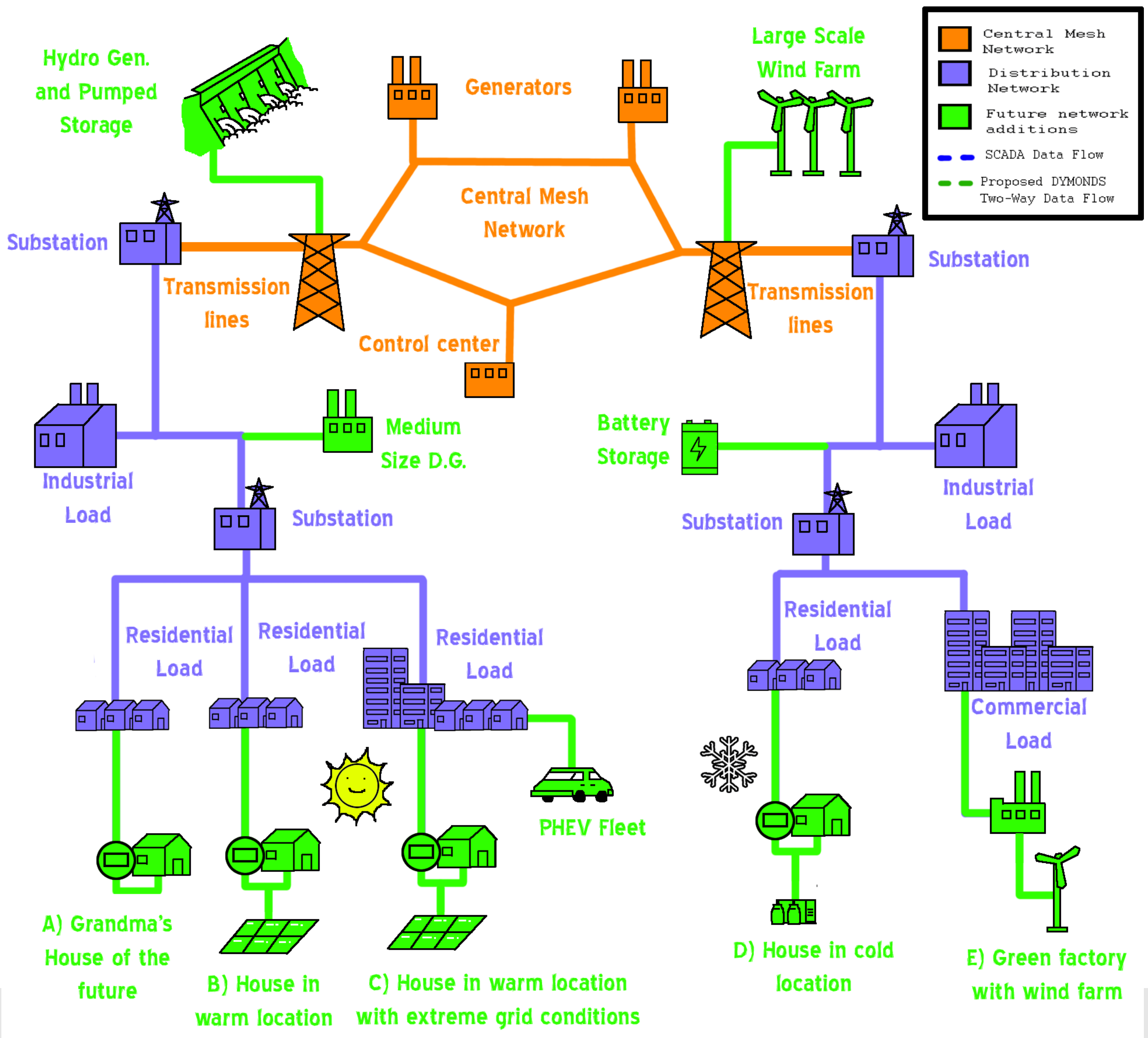
Critical: Transform SCADA

- 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.

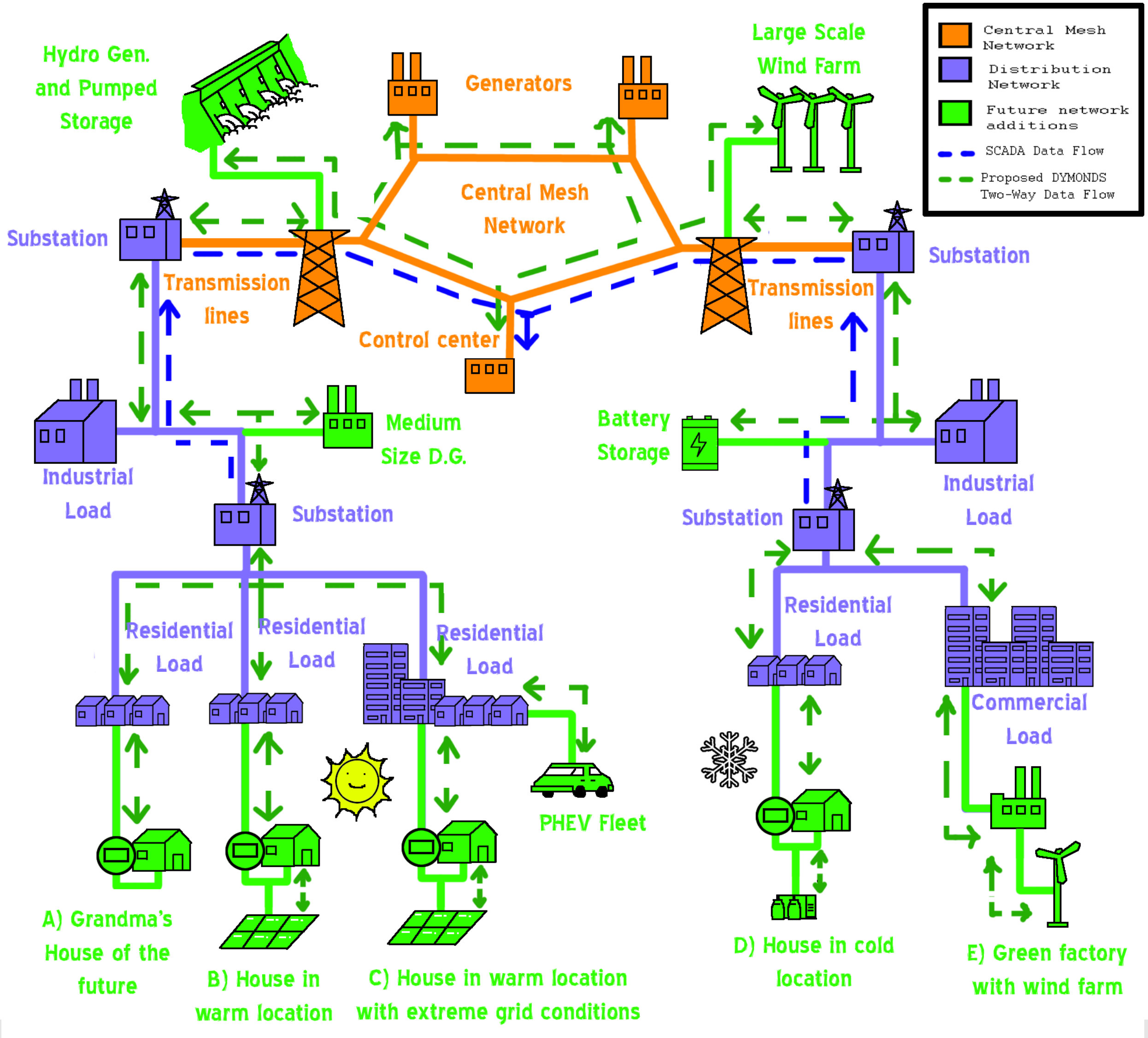
Basic cyber system today –backbone SCADA



Future Smart Grid (Physical system)

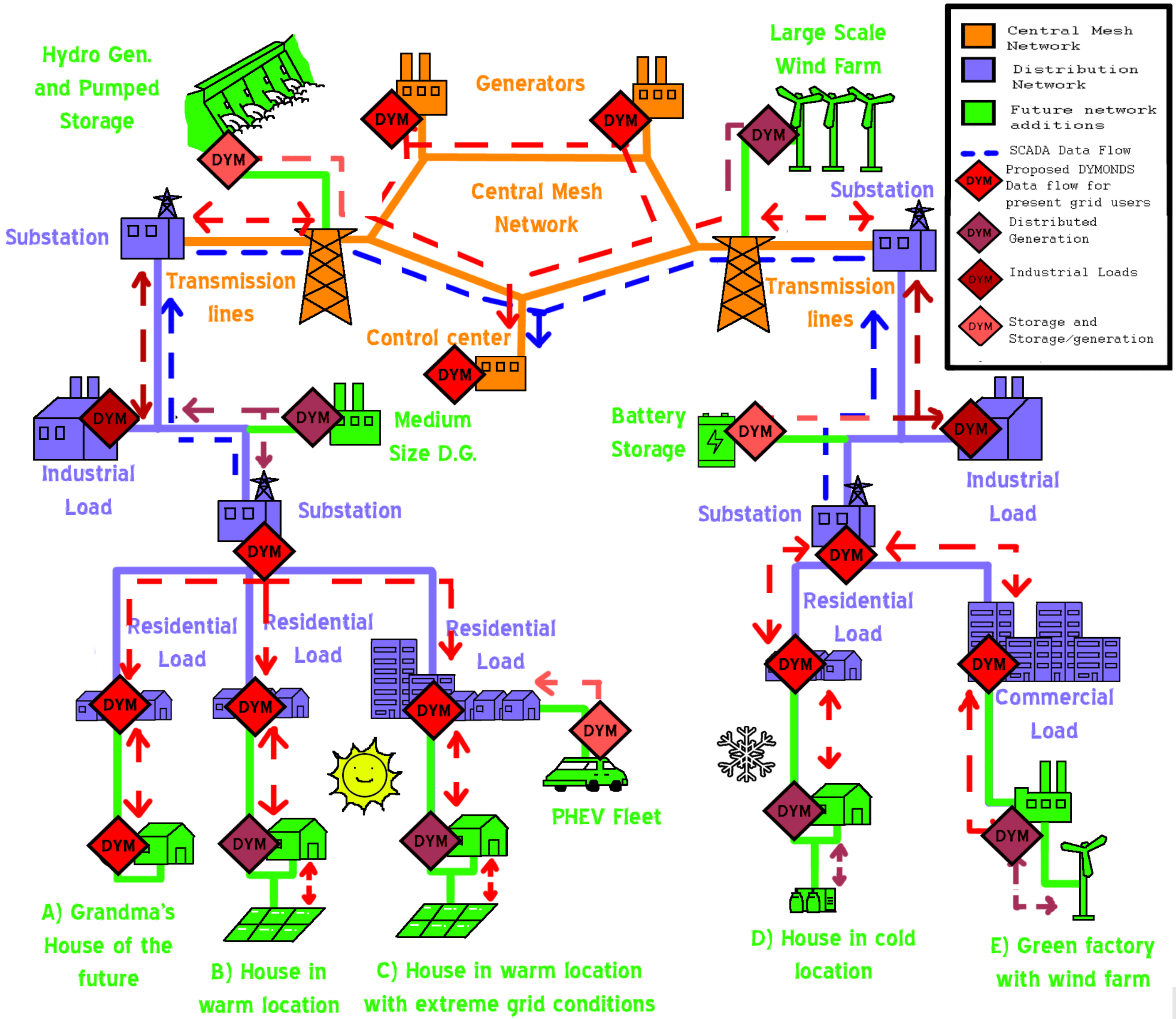


New SCADA

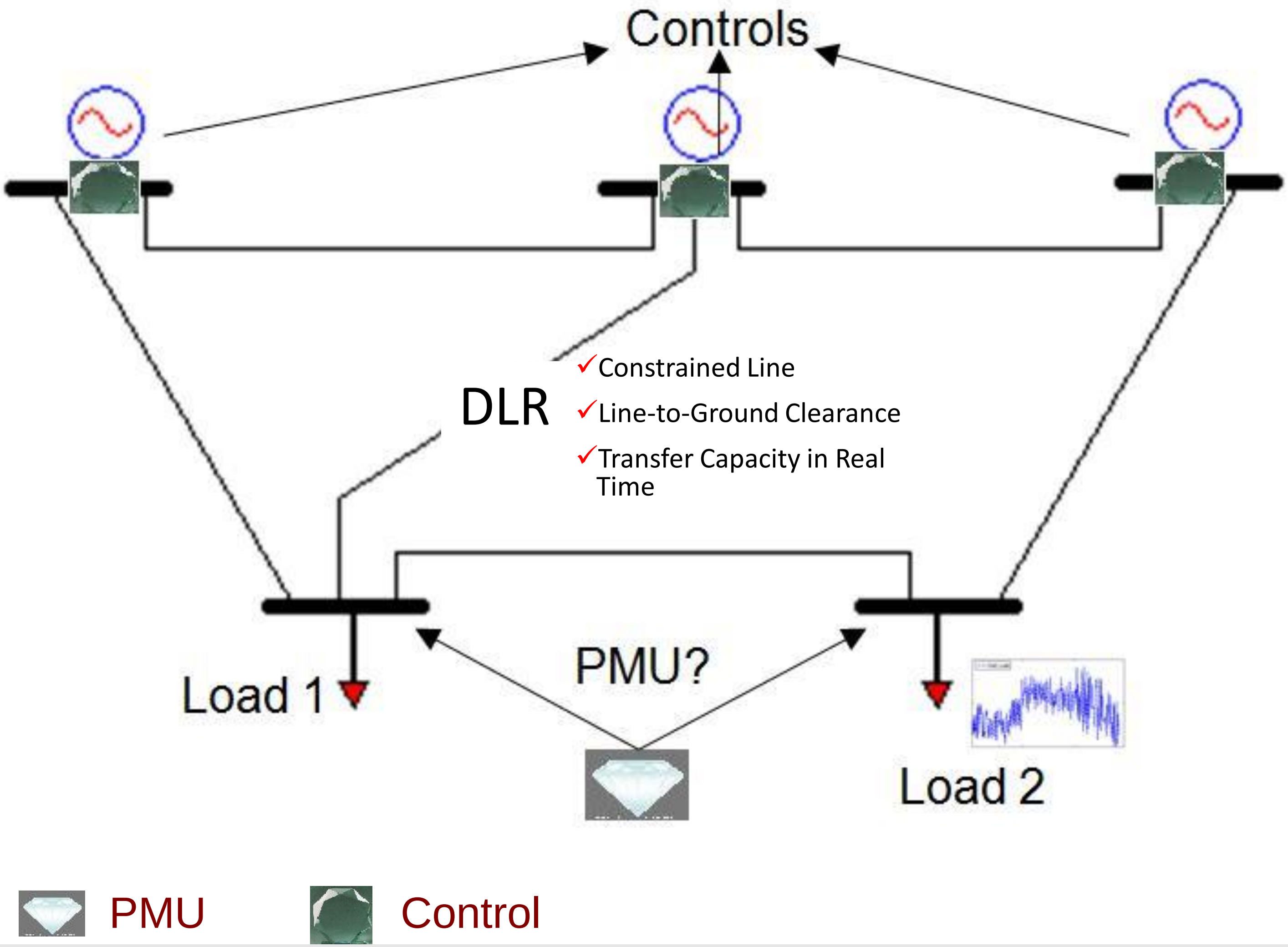


Central Mesh Network
Distribution Network
Future network additions
SCADA Data Flow
Proposed DYMONDS Two-Way Data Flow
Hydro Gen. and Pumped Storage
Generators
Large Scale Wind Farm
Central Mesh Network
Substation
Transmission lines
Control center
Substation
Transmission lines
Industrial Load
Medium Size D.G.
Battery Storage
Industrial Load
Substation
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



On-line automated regulation



Possible dynamical problems seen by particular dynamic components-need for interactive protocols

	Dynamical problems							
		Small signal instab.	Transient instab.	SS R	SSCI	Freq. instab.	Volt. Instab.	Power flow imbalance
Types of Component	Synchronous generators	?	?	?	?	?	?	?
	Wind generators	?	?	?	?	?	?	?
	Solar plants	?	?	?	?	?	?	?
	FACTS	?	?	?	?	?	?	?
	Storage	?	?	?	?	?	?	?

Table 1.

Q2: Can we have a unifying theoretically sound approach to TCP/IP like standards for smart grids?

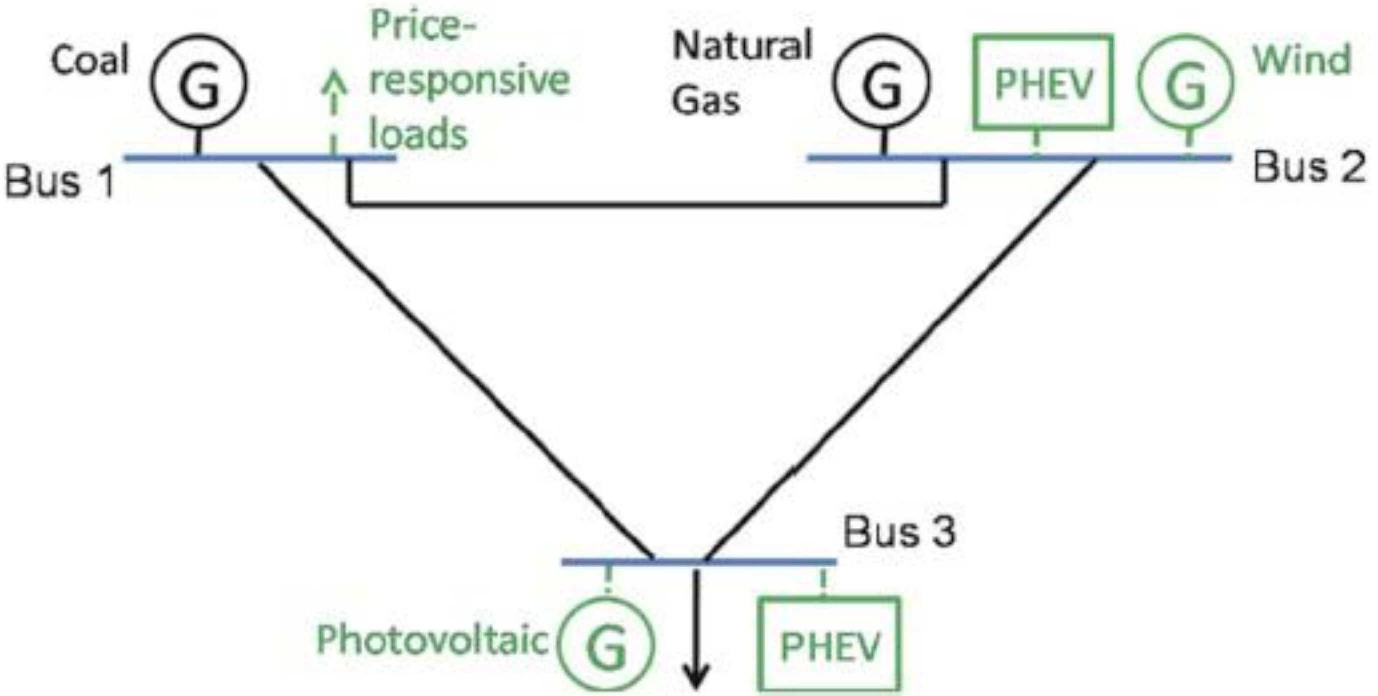


Fig. 5. Small example of the future electric energy system.

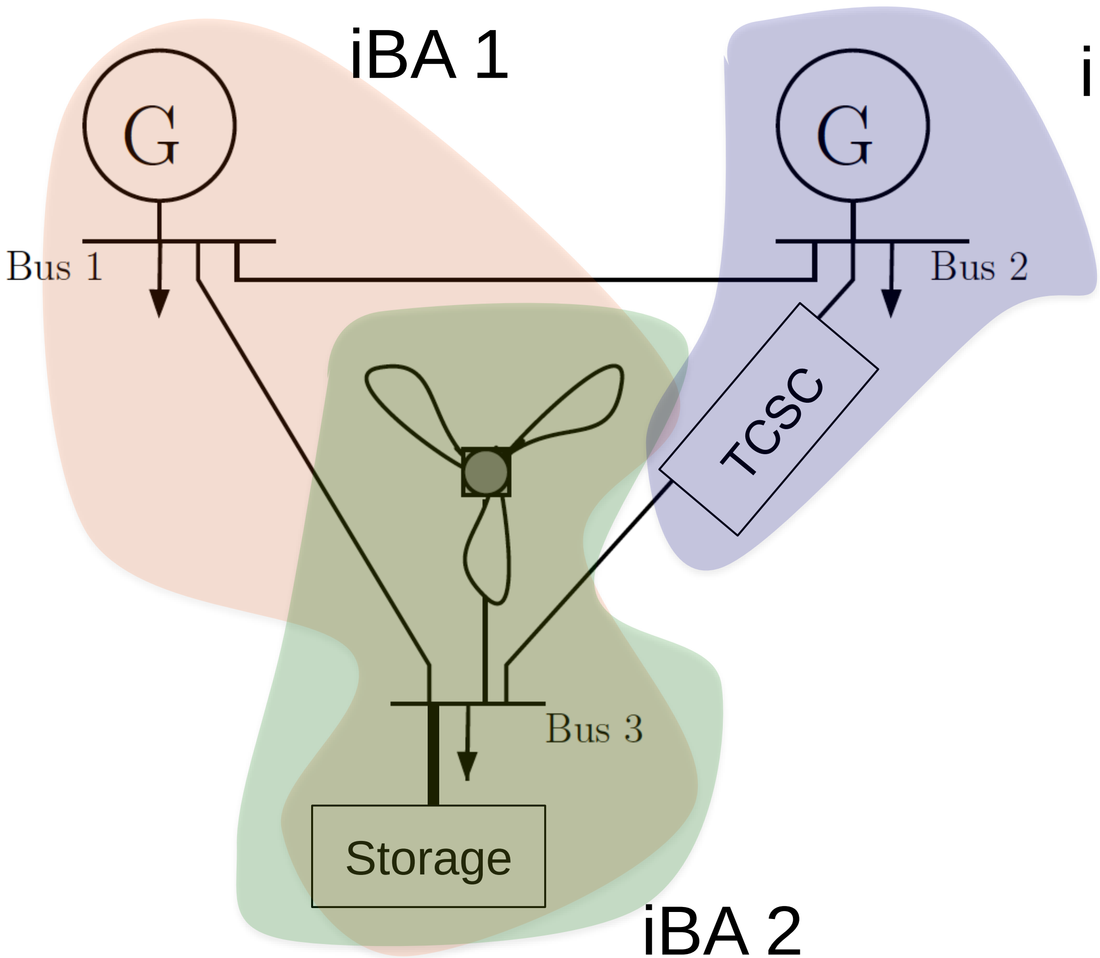
Our proposal: TCP/IP like standards

- Given **specified disturbances and range of operating conditions within a known system**: (1) specified with e.g voltage, power; (2) similar to LVRT curves for wind turbine; (3) with specified duration

- **All components** (synchronous gens, wind gens) **should guarantee** that they would not create any of the problems in Table 1. (Clear objectives goals for components, assigned responsibility for system reliability)

- Two key **questions**: Q1-- Why does it matter? Q2)--- Can this be technically done?

A1: Examples of iBAs—it matters for ensuring both reliable and efficient operations [5,6]

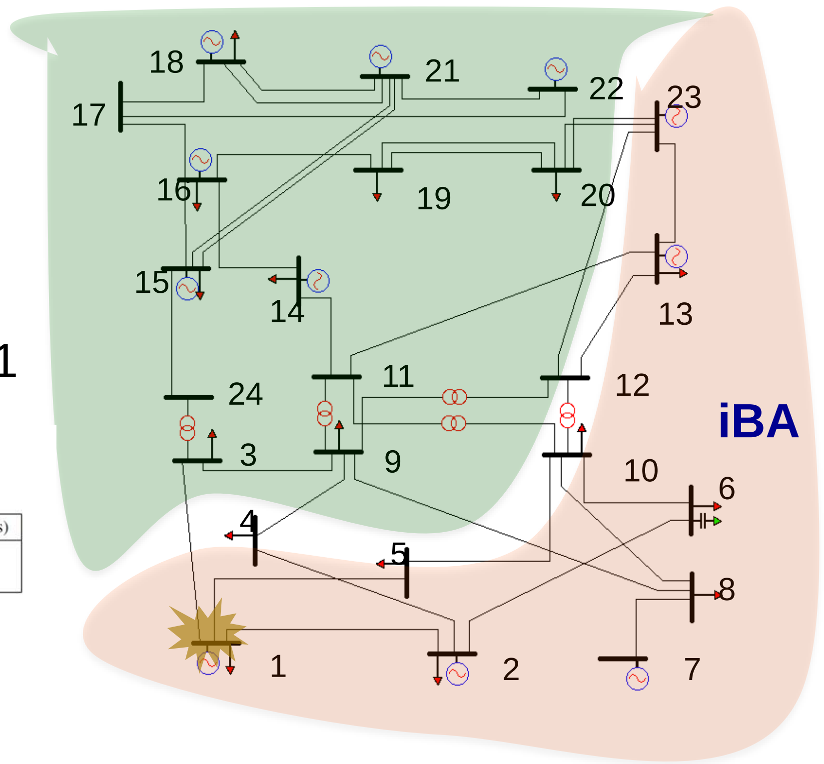


Possible to create iBAs for meeting transient stability distributed standard

Given disturbance
Tripping of generator 1

TABLE I
CONTINGENCY CONSIDERED ON THE IEEE RTS 24 BUS SYSTEM

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

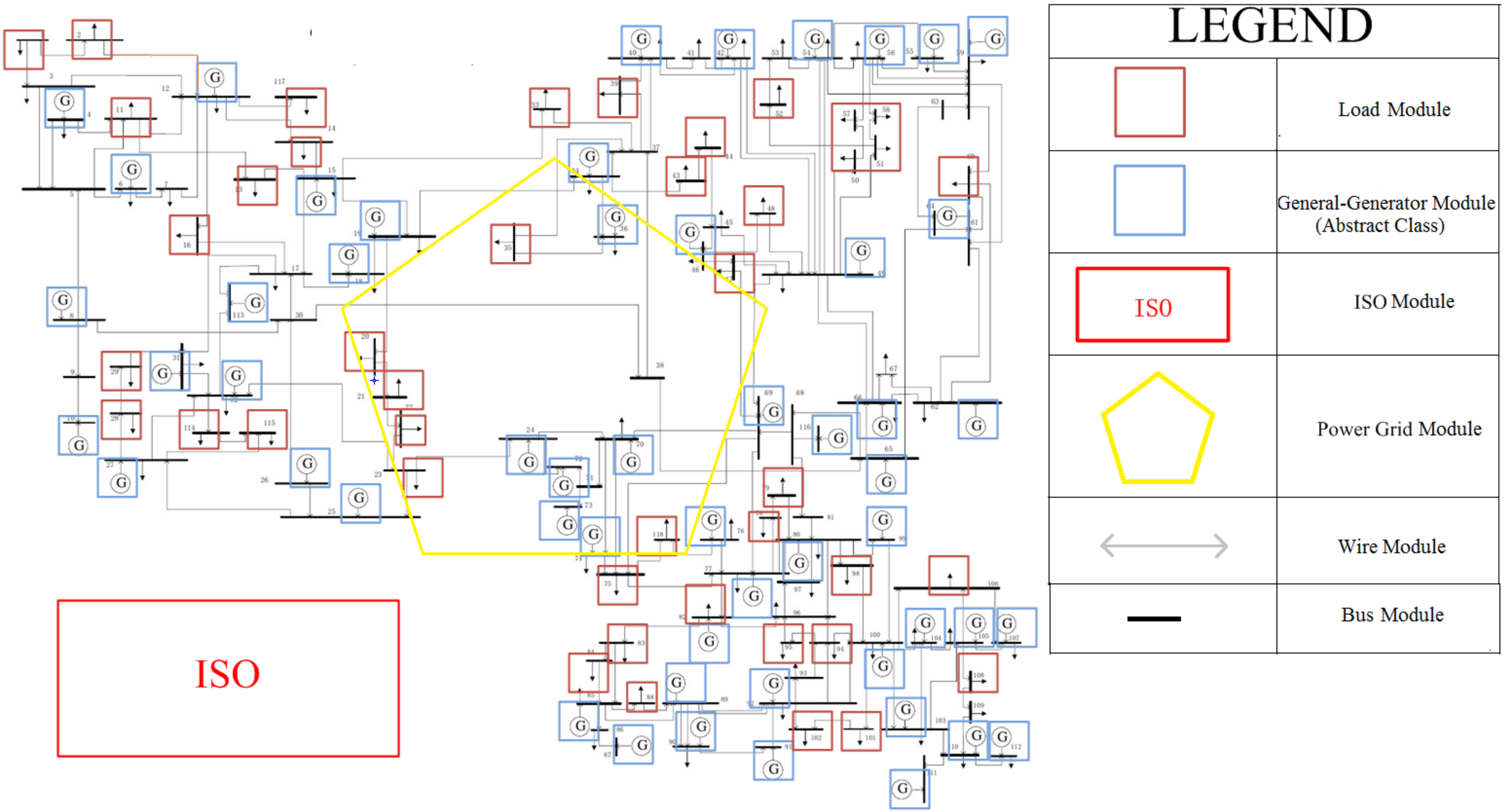


S.Baros, M.Ilic intelligent Balancing Authorities (iBAs) for Transient Stabilization of Large Power Systems IEEE PES General Meeting 2014

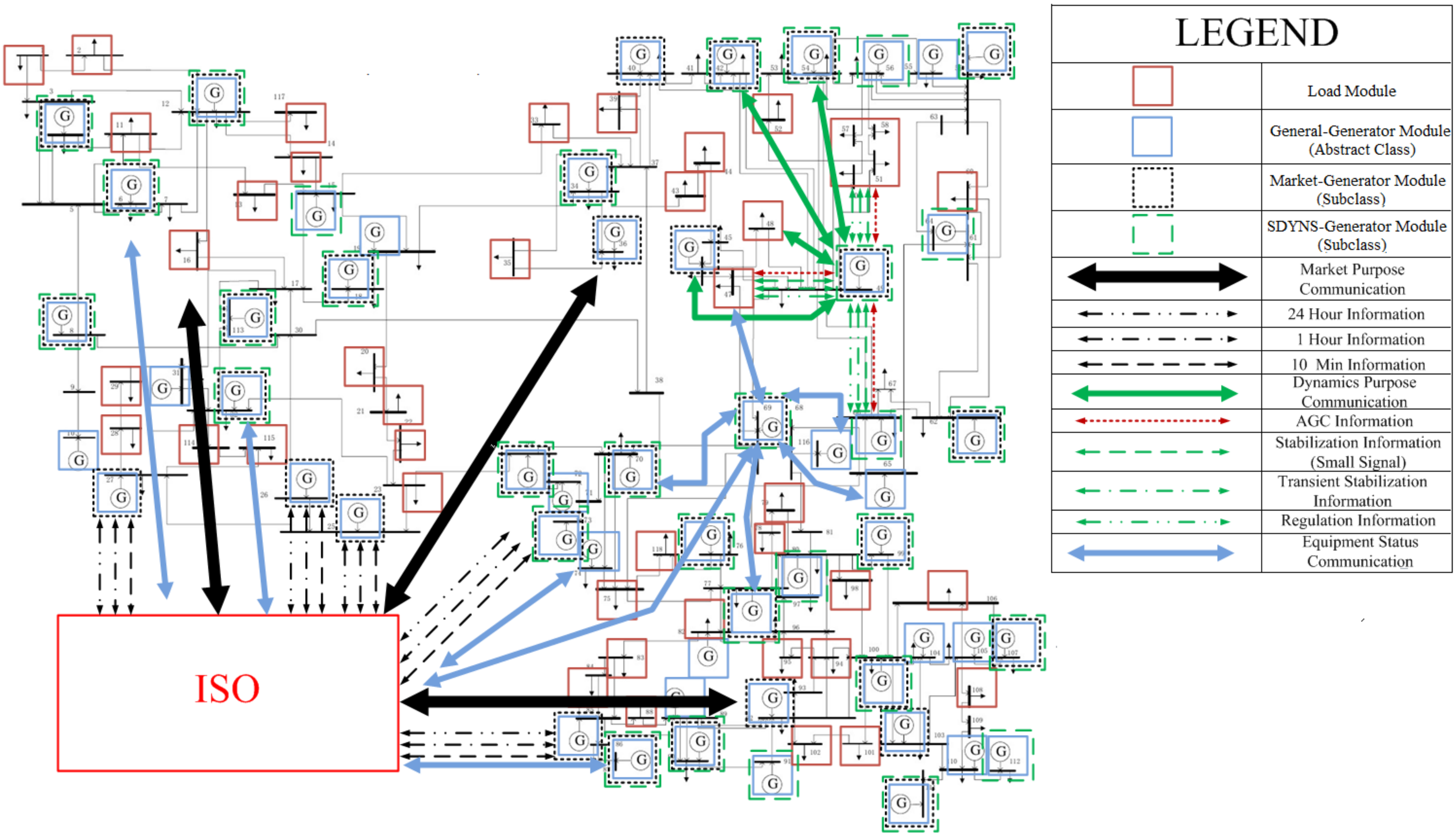
Smart Grid in a Room Simulator

- Uses the same modeling principles; interaction variables for muli-layering
- Basis for scalable interactive simulations-based test-bed—Smart Grid in a Room Simulator (SGRS)—cooperative effort with NIST (demos transactive energy (TE) market simulator—both responsive demand and EVs; transient stabilization of flywheels; variable speed drives (VSD); FACTS); Version 1 of SGRS open to the communityhttps://www.ece.cmu.edu/~electriconf/slides_2015/
- Cooperative effort with National Institute of Standards (NIST)

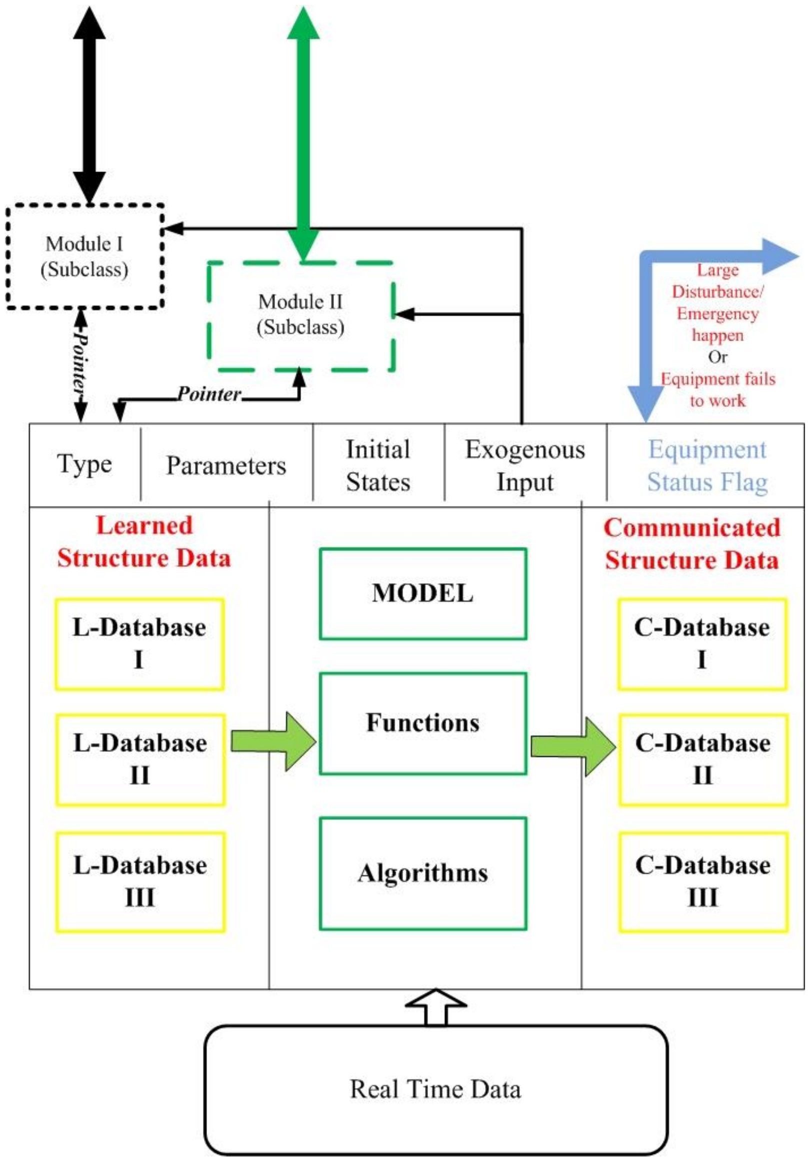
Basis for DyMonDS SGRS



Information Exchange Between Modules

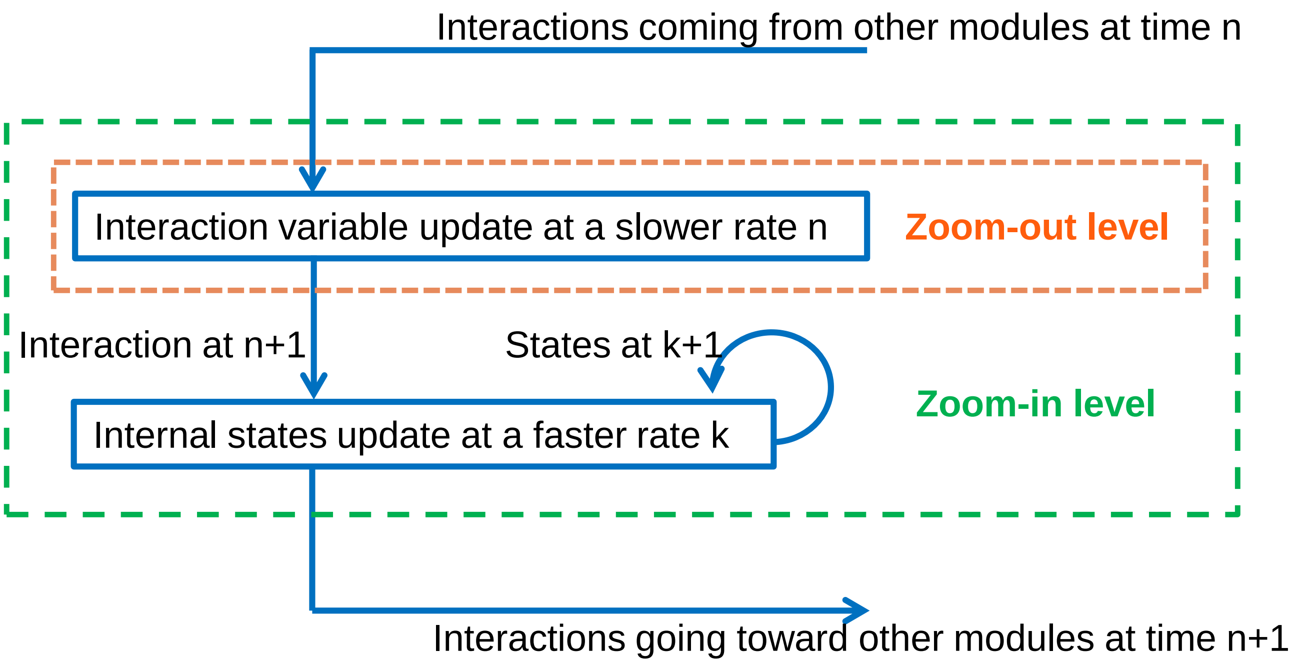


General Module Structure

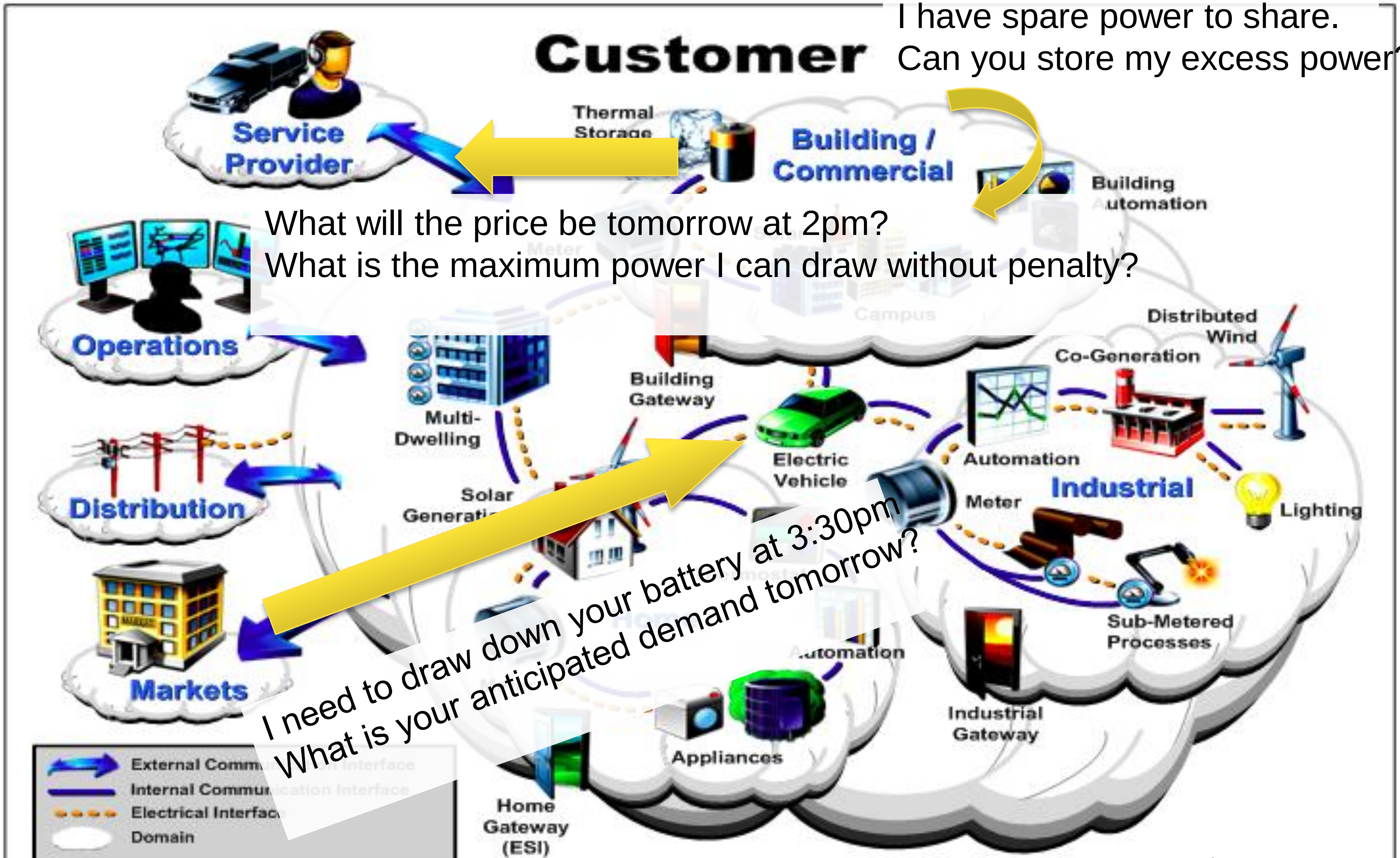


SGRS Hierarchical Distributed Simulation of Dynamics

- Aggregation od dynamics using interaction variables separates the rate of exchange of information and the rate of internal state computations



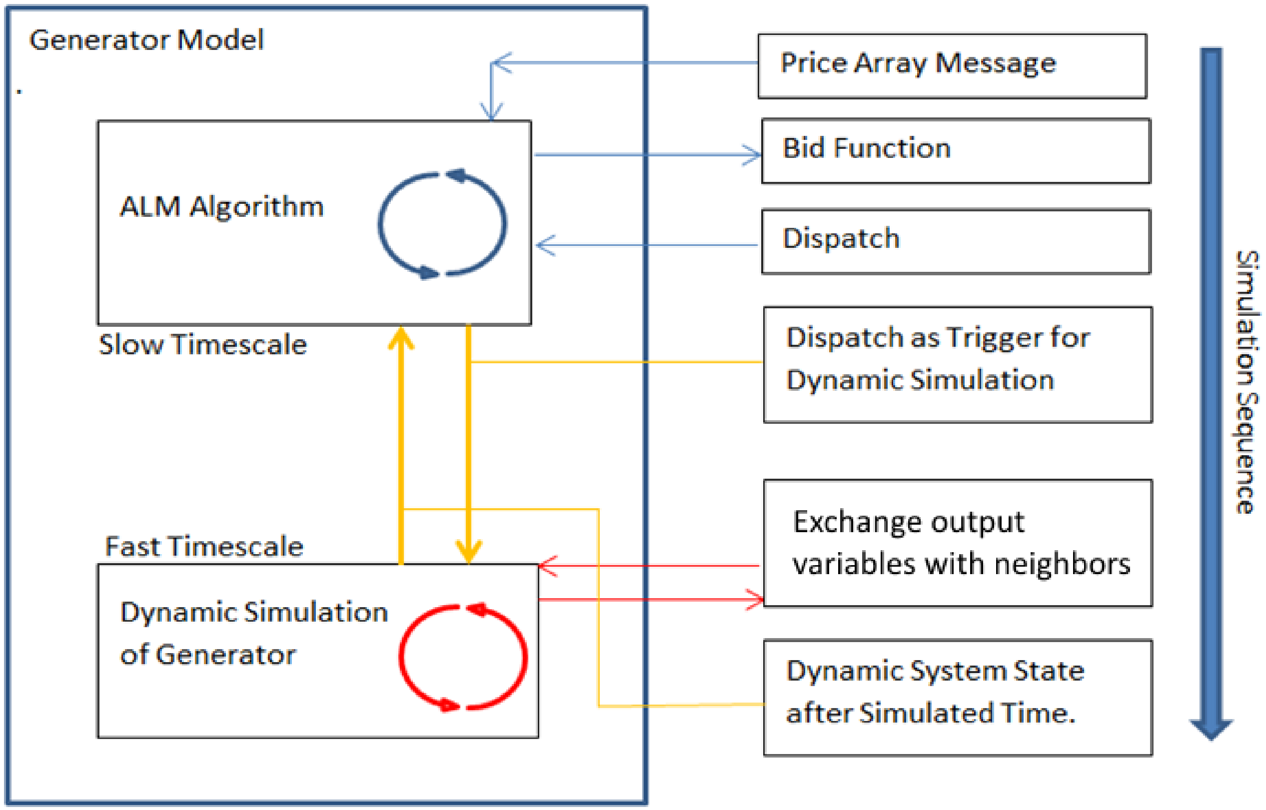
Integration of Smart Consumers (DER)



From NIST Framework Document, SP11

Linking Multi Time-Scale Simulations

- Communication for multi time-scale simulation with ALM and fast dynamics for generators



Source: M. R. Wagner, K. D. Bachovchin, M. D. Ilić, "Computer Architecture and Multi Time-Scale Implementations for Smart Grid in a Room Simulator," EESG Working Paper No. R-WP-1-2014, March 2015.

Concluding remarks

- Physics-based modeling of electric power systems with non-zero mean disturbances
- Multi-layered dynamic models with explicit interaction variables relevant for coordinating levels
- Basis for consistent interactive communication within the multi-layered architecture
- Examples of problems with non-interactive information exchange (potentially unstable markets)
- Examples of enhanced AGC (E-AGC) for consistent frequency stabilization and regulation in response to non-zero mean disturbances
- Examples of fast power electronically switched cooperative control
- General communication protocols for DyMonDS Smart Grid in a Room Simulator (SGRS) based on these models
- The basis for general purpose scalable SGRS to emulate system response in the emerging power systems
- The challenge for user is to change their centralized method to DyMonDS based form

Sample demos using SGRS –Flores island

- Details about SGRS design/user's guide (Martin Wagner; Jovan Ilic)
- Transactive energy market simulator; grid constraints included (Donadee, Joo, Wagner)
- Issues with interfaces (relevance of Q; market created instabilities)
- Simulation of the effects of transient stabilizing nonlinear control using flywheels for wind power plants
- https://www.ece.cmu.edu/~electriconf/presentations.html