Performance Objectives and Models for General Purpose Multi-Layered Testbed Power Systems Simulators

Marija Ilić milic@ece.cmu.edu

Electric Energy Systems Group (EESG) http://www.eesg.ece.cmu.edu/, Director

Presentation for 10th CMU Electricity Conference
https://www.ece.cmu.edu/~electriconf/

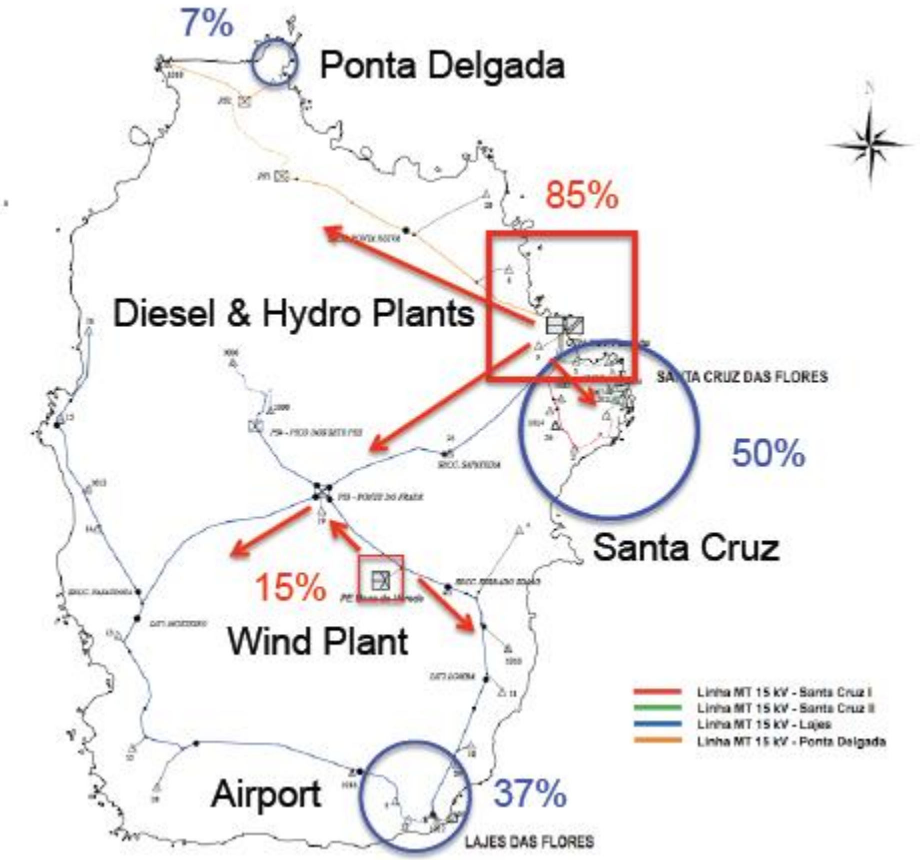
April 1,2015

How It all started—hindsight view

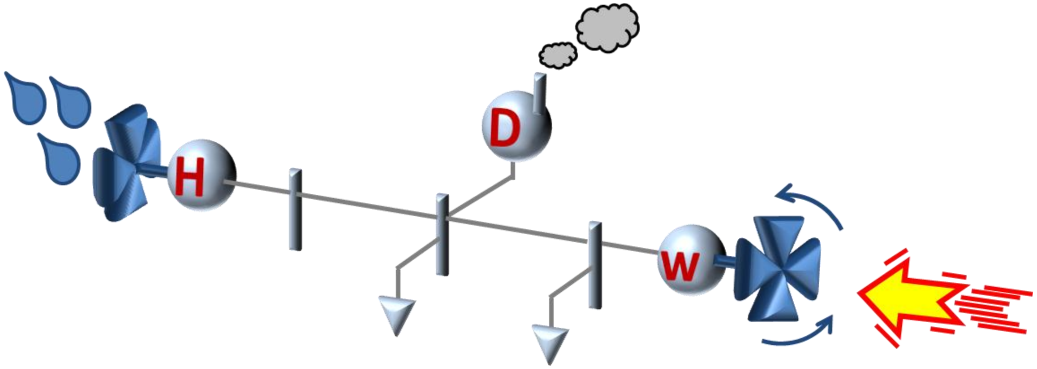
- Innovation in power systems hard and slow
- Outdated assumptions in the new environment
- No simulators to emulate time evolution of complex event driven states
- Fundamental need for more user-friendly innovation/technology transfer
- General simulators (architecture, data driven) vs. power systems simulations (physics-based, specific phenomena separately)
- Missing modeling for provable control design
- Difficult to define performance objectives at different industry layers; coordination of interactions between the layers for system-wide reliability and efficiency ; tradeoff between complexity and performance
- Challenge of managing multiple performance objectives

- EESG Ilic group http://www.eesg.ece.cmu.edu/
- Dynamic Monitoring and Decision Systems (DyMonDS) framework for enabling smart SCADA; direct link with sustainability (enabler of clean, reliable and efficient integration of new resources); main role of interactive physics –based modeling for IT/cyber
- Cooperative effort with National Institute of Standards (NIST) for building Smart Grid in a Room Simulator (SGRS)
- ***Recent new unifying modeling in support of DyMonDS***

From old to new paradigm—Flores Island Power System, Portugal



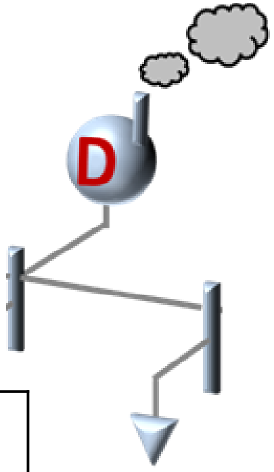
Controllable components—today's operations (very little dynamic control, sensing)



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
	0.3071
	0.1695

Base values

$S_b = 10MVA$

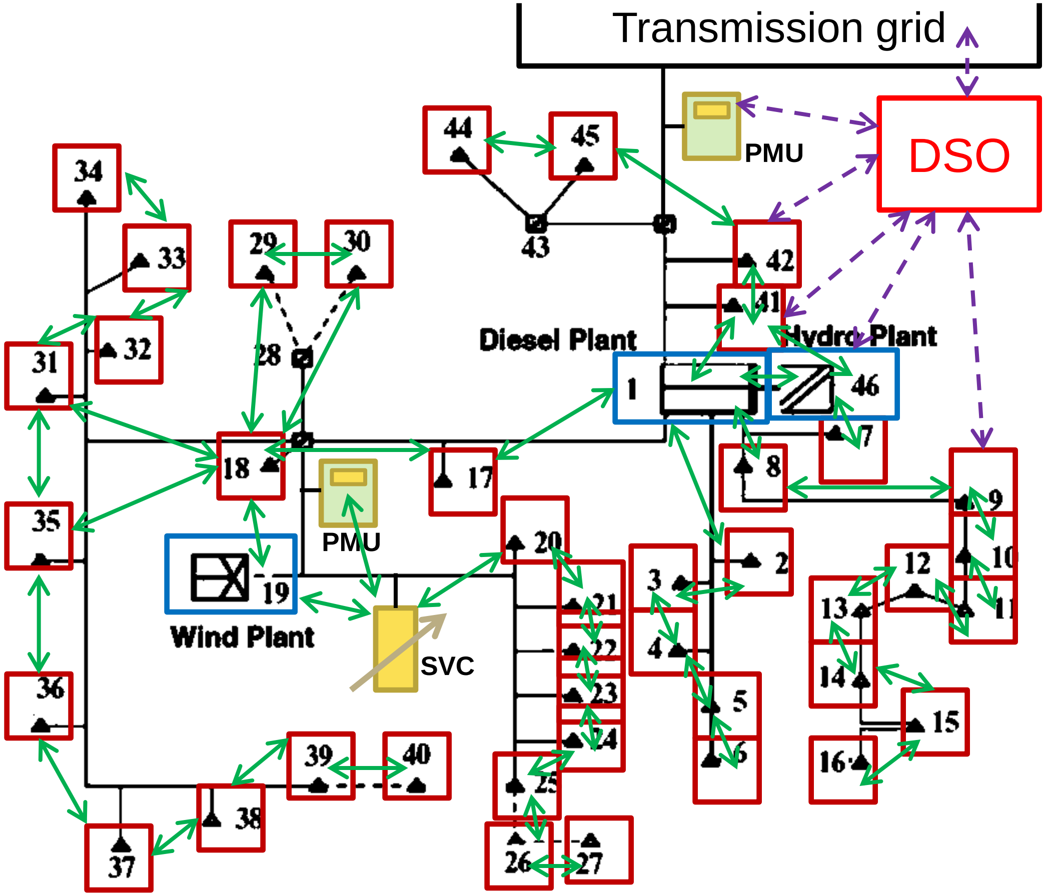
$V_b = 15KV$

AVR	Diesel
	400
	0.02
	1.3
	1
	0.1667
	0.03
	1

Governor	Diesel
	40
	0.6
	1/0.03
	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)



LEGEND	
🟥	Load Module
🟦	General-Generator Module (Abstract Class)
DSO	DSO Module
—	Wire Module
▨	Power-electronics Module
▨	Phasor Measurement Units
⟷	Dynamic Purpose Communication
⇠ - - - ⇢	Market and Equipment Status Communication

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

Comparison of today's and emerging dynamic systems

- Small system example
- Qualitatively different disturbances require different dynamic models
  - Case 1: zero mean disturbance; static load model
  - Case 2: non zero mean disturbance; load a dynamic distributed energy resource (DER)
- **Short summary of modeling assumptions for today's hierarchical control** (**Case 1**)
- Critical issues with static load modeling and its implications on system feasibility
  - Importance of Q
- Critical issues with non zero mean disturbance
  - Steady state 60 Hz and nominal voltage assumption may not hold
- **Proposed unifying dynamic modeling –Basis for DyMoNDS** (**Case 2**)
  - All components are dynamic (ODEs; discrete time models); based on systematic temporal model reduction
  - Has inherent spatial structure (multi-layered interactive models)
  - Interactive information exchange (no longer top-down only) to ensure consistent implementation of multi-layered control architecture

Case 1: zero mean disturbance & static load model

- Assumed zero-mean deviation from prediction → equilibria conditions

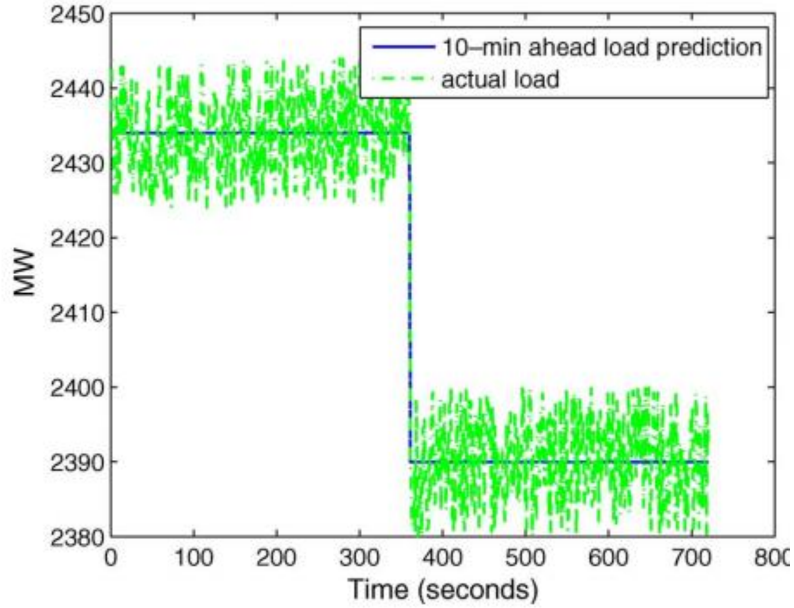


Fig. 3. ***10-min-ahead load prediction and second-by-second actual load.***

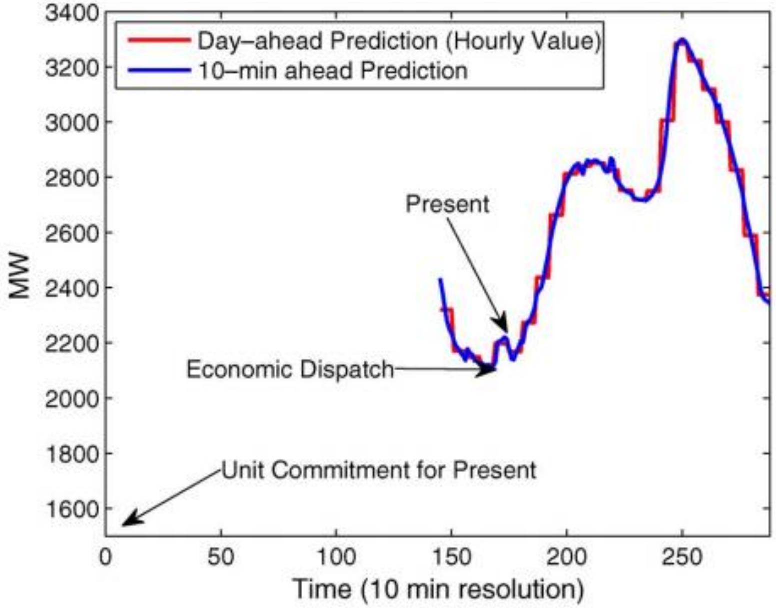


Fig. 2. ***Day-ahead and 10-min-ahead load prediction, and timing of UC and ED functions.***

$$L(t) = \hat{L}[H] + \Delta_{LH}(t)$$

$$L(t) = \hat{L}[k] + \Delta_{Lk}(t)$$

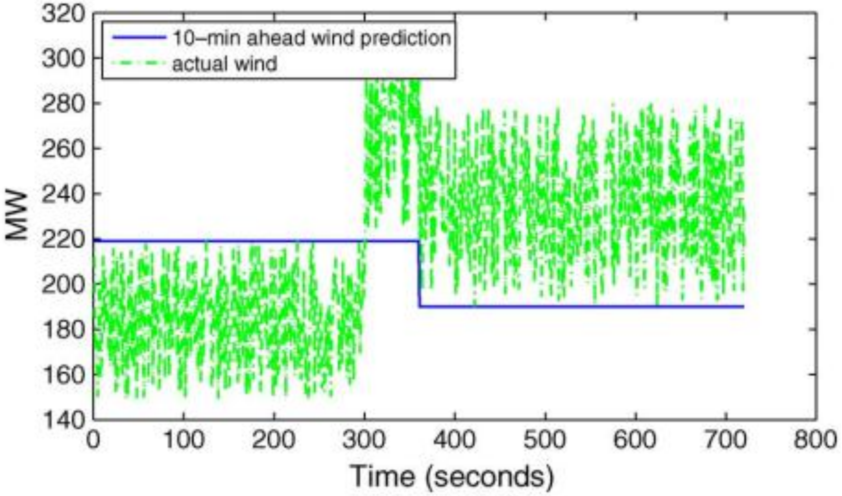
$$\|\hat{L}[H]\| \gg \|\Delta_{LH}(t)\|$$

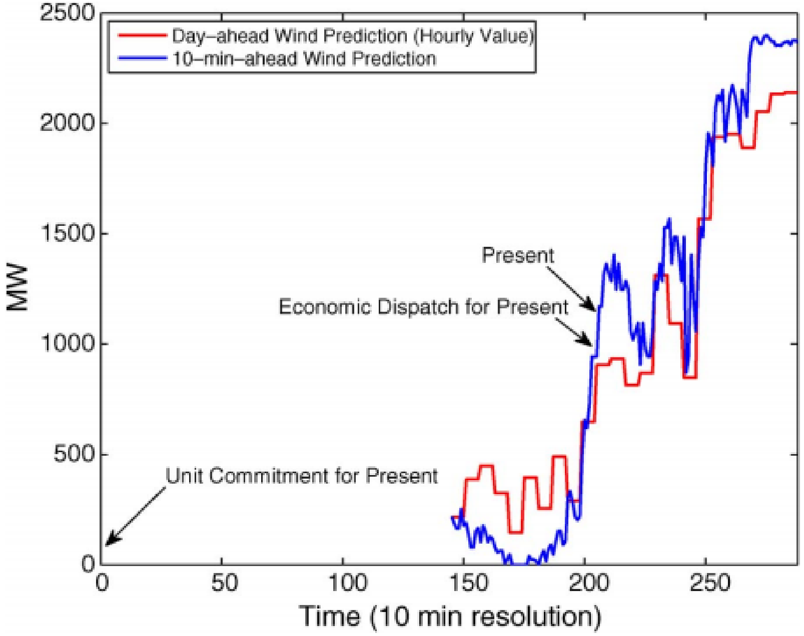
$$\|\Delta_{LH}(t)\| > \|\Delta_{Lk}(t)\|.$$

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.

Wind power disturbance – multiple time scales

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





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

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

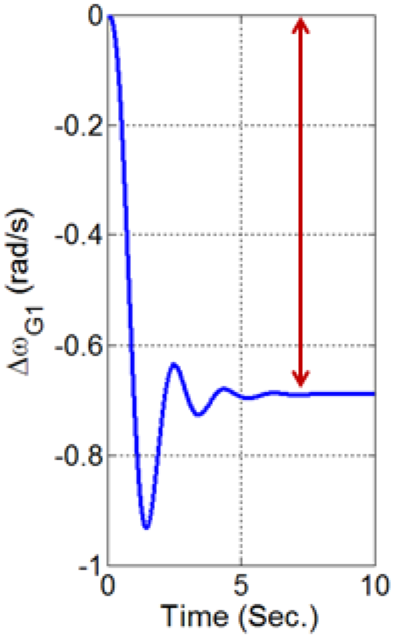
$$\|\Delta_{Gw_H}(t)| \gg \|\Delta_{Gw_k}(t)\|$$

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

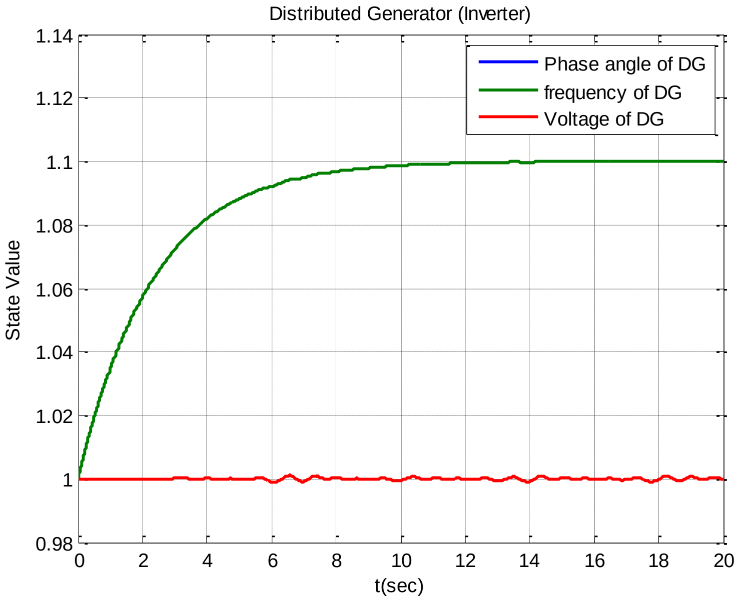
Xie, L., Carvalho, P. M., Ferreira, L. A., Liu, J., Krogh, B. H., Popli, N., & Ilic, M. D. (2011). Wind integration in power systems: Operational challenges and possible solutions. *Proceedings of the IEEE*, *99*(1), 214-232.

Fundamental effect of non-zero mean disturbance

- 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]



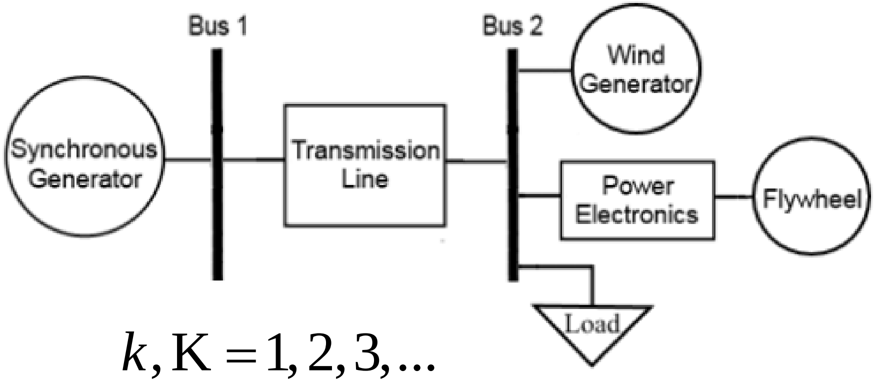
[2]Q. Liu. Wide-Area Coordination for Frequency Control in Complex Power Systems. Ph.D. Thesis, CMU, Aug 2013.
[3] X. Miao, M. Ilic. EESG working paper, 2015

DyMonDS modeling for simulations

- On the Flores island when one replaces PQ load with a DER/storage and its control
- Multi-temporal, multi-spatial and interactive to simulate the response of the system to multi-rate disturbances
- Show the effect of embedded distributed control (multi-temporal, multi-layered) on closed-loop response

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

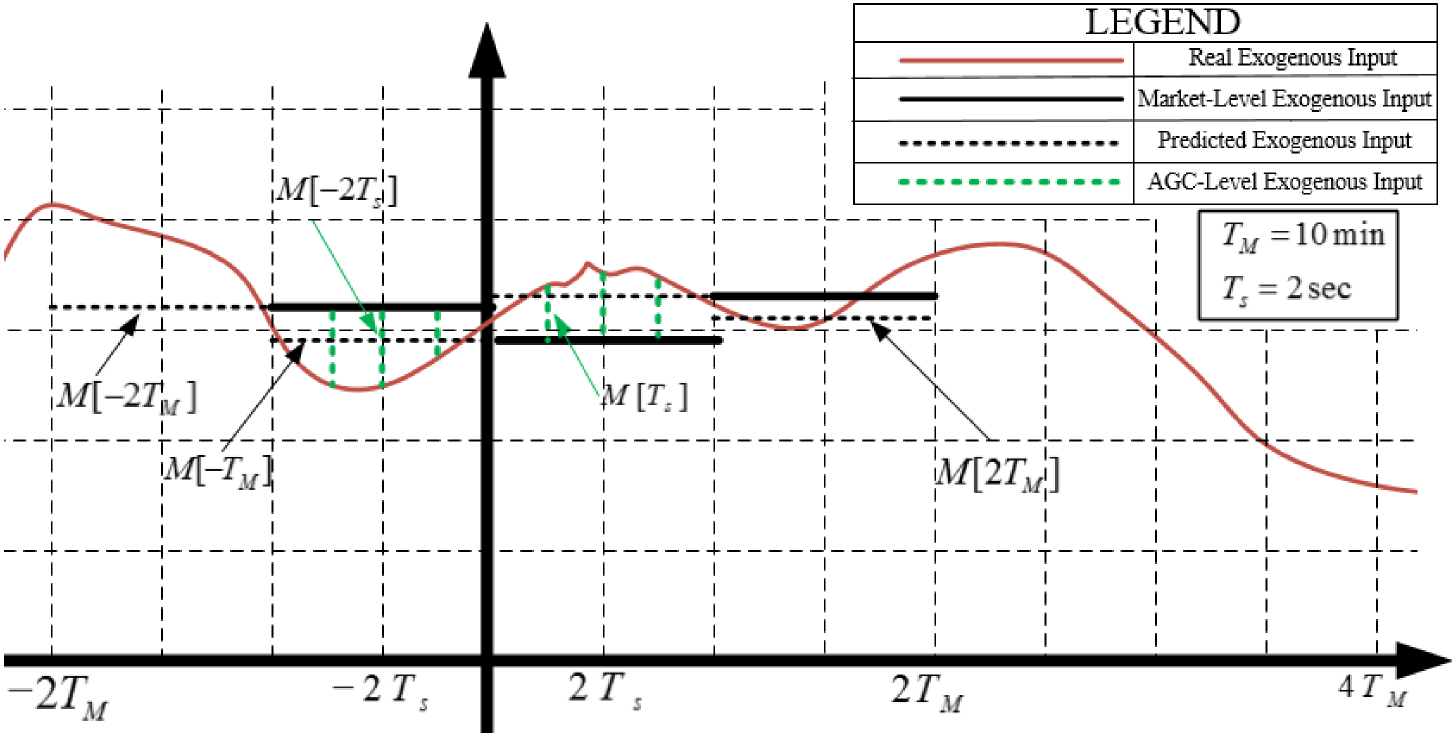
$x_j(t)$ – State variable of Module j, $j \in C_i$

$$k, \mathrm{K} = 1, 2, 3, \ldots$$
$$T_M = 10\,\text{min}, 1\text{ hour, 24 hour}$$
$$T_s = 1 - 60\,\text{sec}$$

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

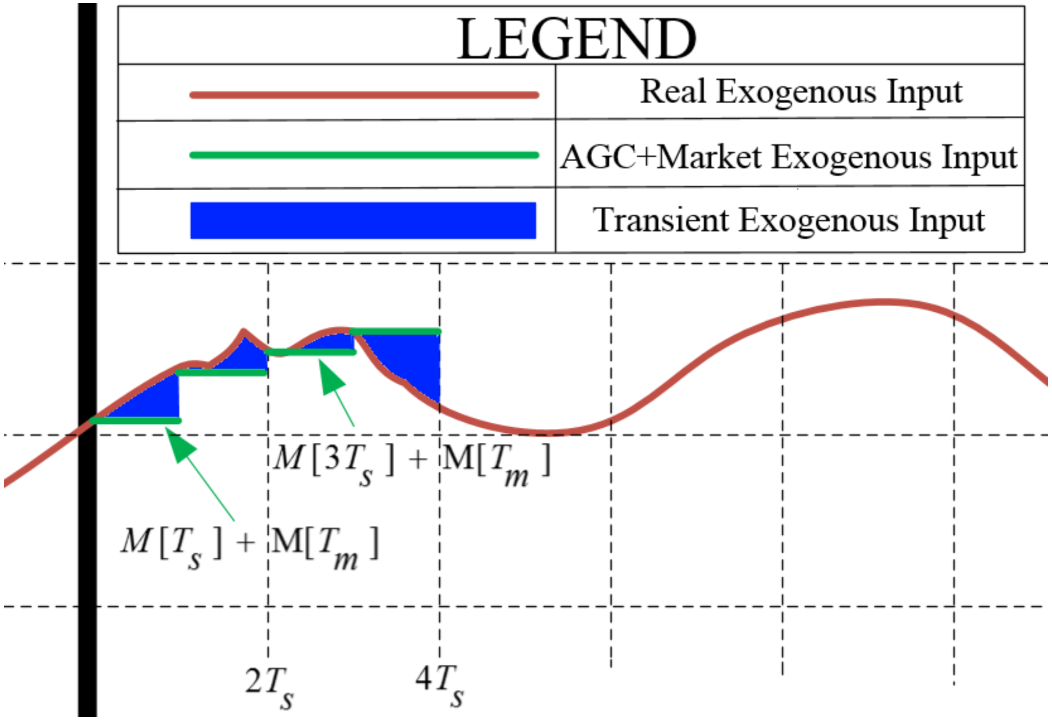
$$u_i = \underbrace{\boxed{u_i(t)}}_{\text{Local}} + \underbrace{\boxed{u_i^{ref}\left[k \cdot T_s\right]}}_{\text{AGC}} + \underbrace{\boxed{u_i^{ref}\left[k \cdot T_M\right]}}_{\text{Market}}$$

Multi-temporal exogenous input – Zoom Out



$$\underbrace{m_i(t)}_{\text{Real Exogenous Input}} = \underbrace{M_i[K \cdot T_M]}_{\text{Market-Level Exogenous Input}} + \underbrace{M_i[k \cdot T_s]}_{\text{AGC-Level Exogenous Input}} + \underbrace{\Delta m_i(t)}_{\text{Transient Exogenous Input}}$$

Multi-temporal exogenous input – Zoom In



$$\underbrace{m_i(t)}_{\text{Real Exogenous Input}} = \underbrace{M_i[K \cdot T_M]}_{\text{Market-Level Exogenous Input}} + \underbrace{M_i[k \cdot T_s]}_{\text{AGC-Level Exogenous Input}} + \underbrace{\Delta m_i(t)}_{\text{Transient Exogenous Input}}$$

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)	driven by controlled by	driven by and controlled by	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

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

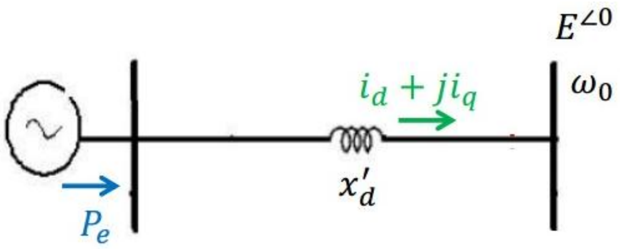
Interaction level model for coordination

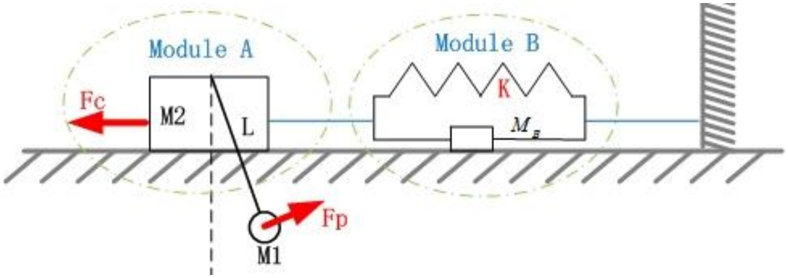
$$\dot{Z}_A = f_{ZA}\left(\bar{\bar{X}}_A, Z_A, P_B\right)$$

$$\dot{P}_A = f_{PA}\left(\bar{\bar{X}}_A, P_A, \dot{P}_B\right)$$

$$\dot{Z}_B = f_{ZB}\left(Z_B, P_A, u_B\right)$$

$$\dot{P}_B = f_{PB}\left(P_B, \dot{P}_A\right)$$

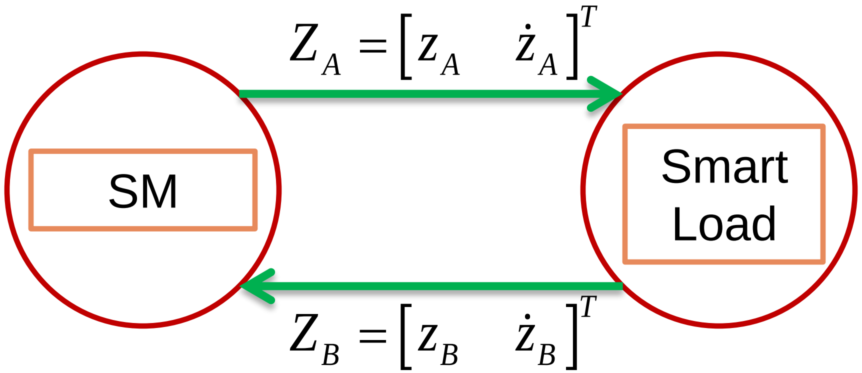


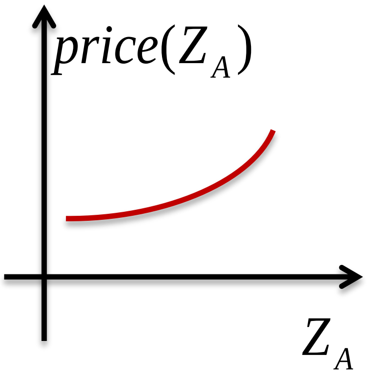


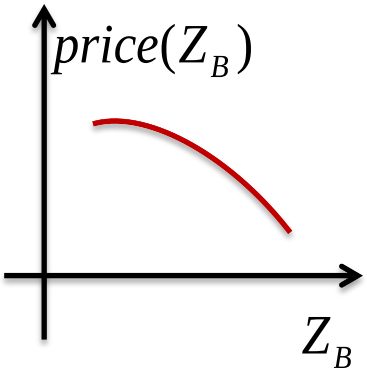
- Less assumption and communication are needed;
- System dynamics are separated into multi-layer system: internal layer and interaction layer;
- Based on above frame work, different control strategy can be used and designed: competitive or cooperative control

Required information exchange for interconnected system

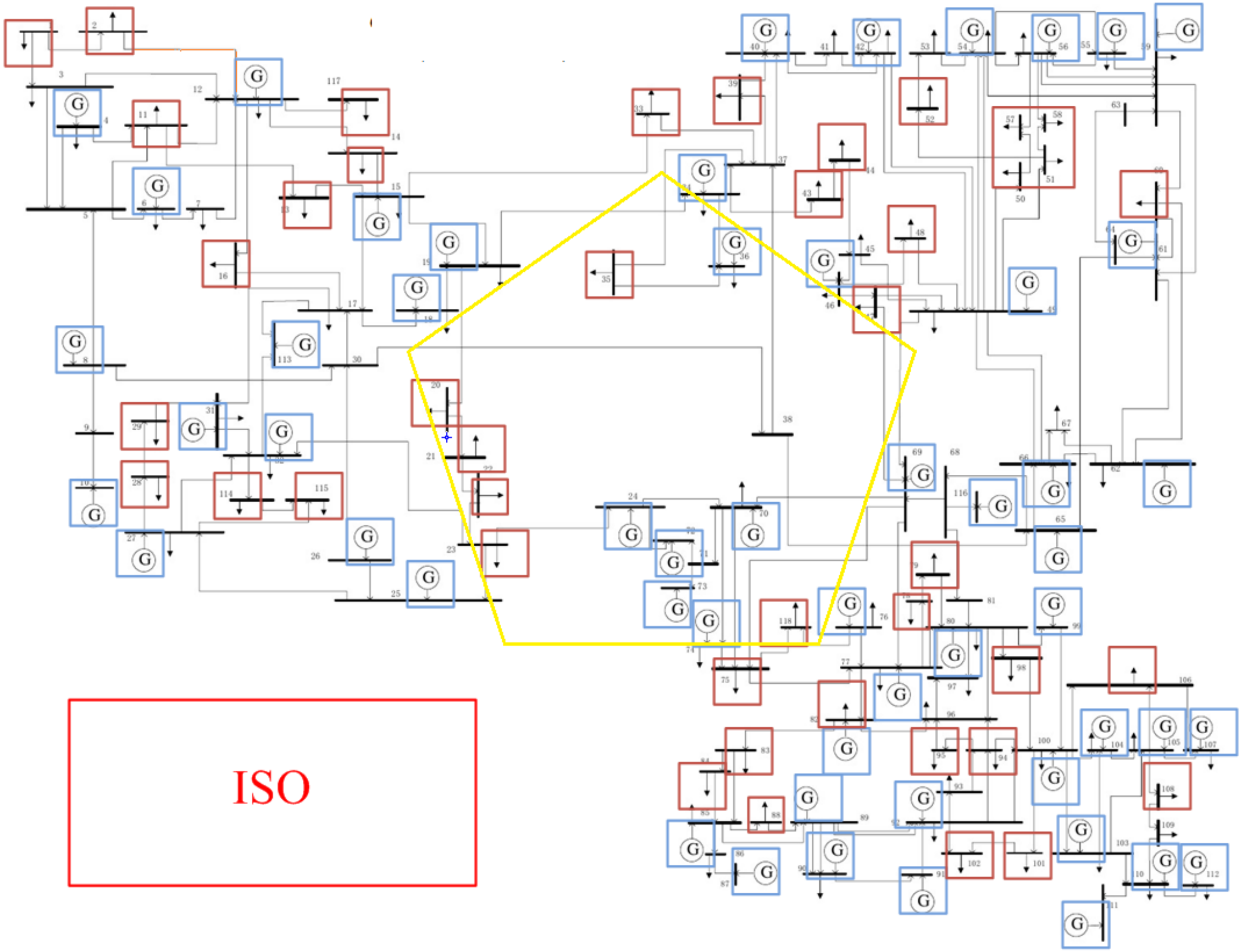
- To ensure reliability (stability, feasibility)
    - Must be exchanged interactively. They represents the total incremental energy & its rate of change; In steady state, decoupled assumption will be ***P & Q***
    - Ranges (convex function) instead of points exchanged (DyMonDS)
- For distributed interactive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





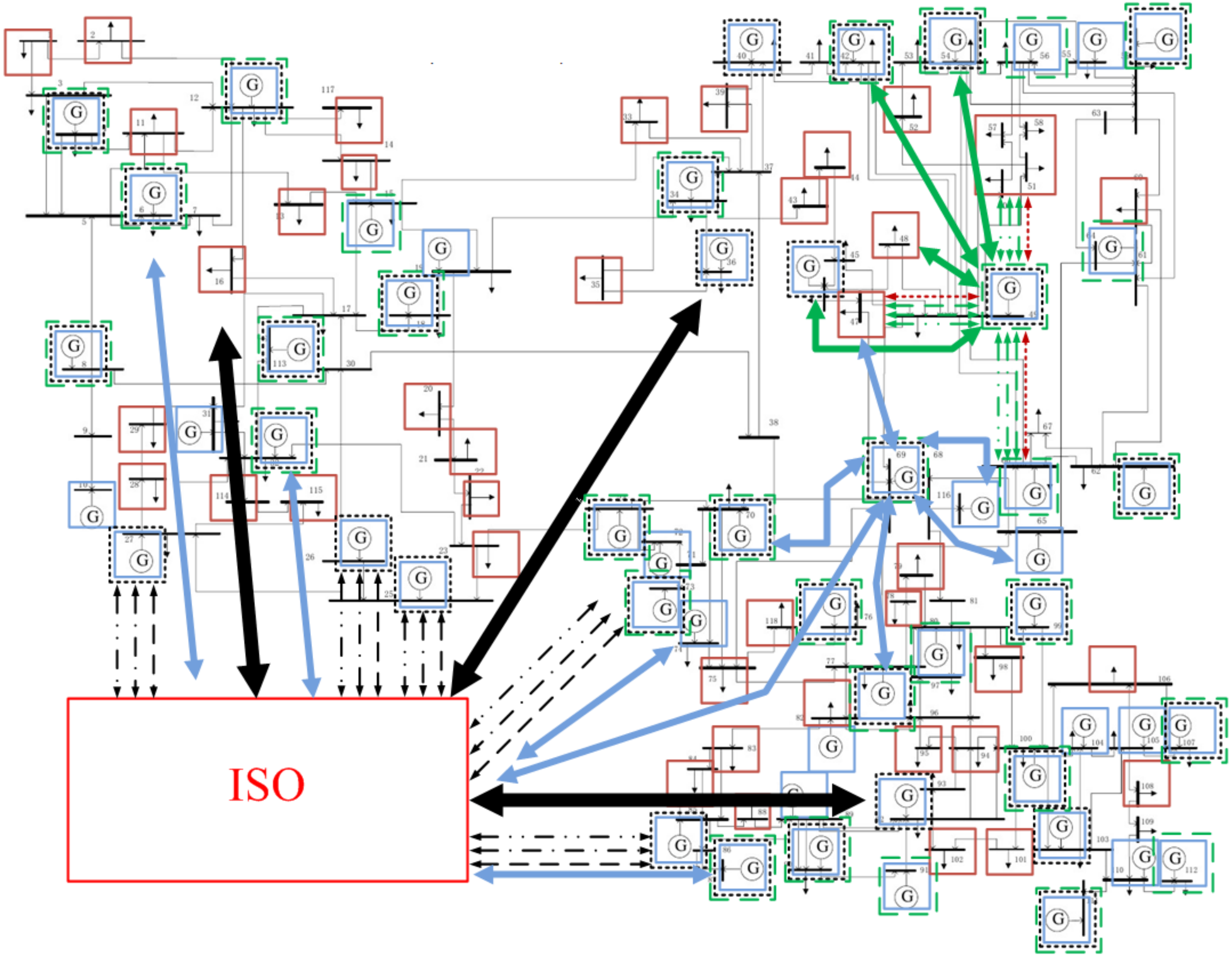


Basis for DyMonDS SGRS



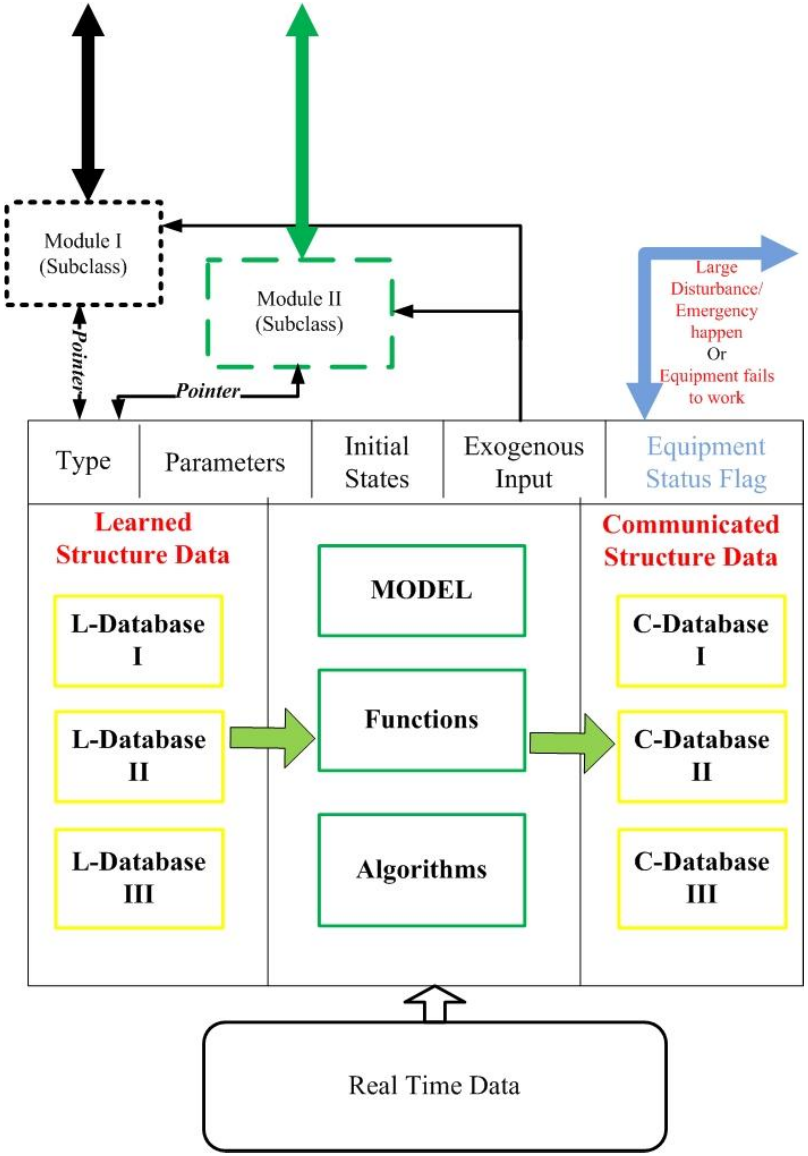
LEGEND	
🟥	Load Module
🟦	General-Generator Module (Abstract Class)
ISO	ISO Module
⬠	Power Grid Module
↔	Wire Module
▬	Bus Module

Information Exchange Between Modules

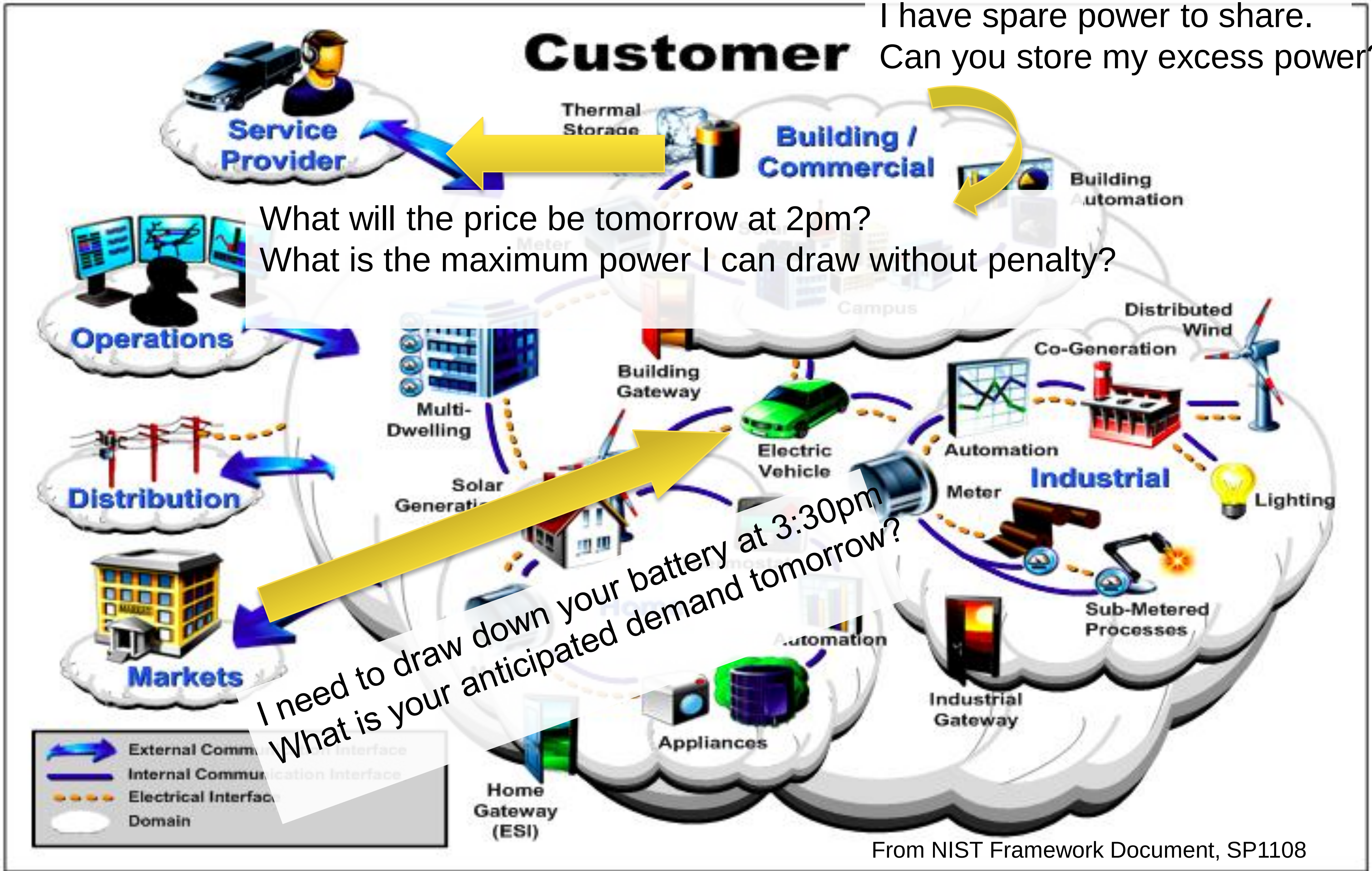


LEGEND	
☐	Load Module
☐	General-Generator Module (Abstract Class)
⬚	Market-Generator Module (Subclass)
⬚	SDYNS-Generator Module (Subclass)
⟷	Market Purpose Communication
⟷	24 Hour Information
⟷	1 Hour Information
⟷	10 Min Information
⟷	Dynamics Purpose Communication
⟷	AGC Information
⟷	Stabilization Information (Small Signal)
⟷	Transient Stabilization Information
⟷	Regulation Information
⟷	Equipment Status Communication

General Module Structure



Integration of Smart Consumers (DER)



I have spare power to share.
Can you store my excess power

What will the price be tomorrow at 2pm?
What is the maximum power I can draw without penalty?

I need to draw down your battery at 3:30pm
What is your anticipated demand tomorrow?

From NIST Framework Document, SP1108

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

Thank you & Questions