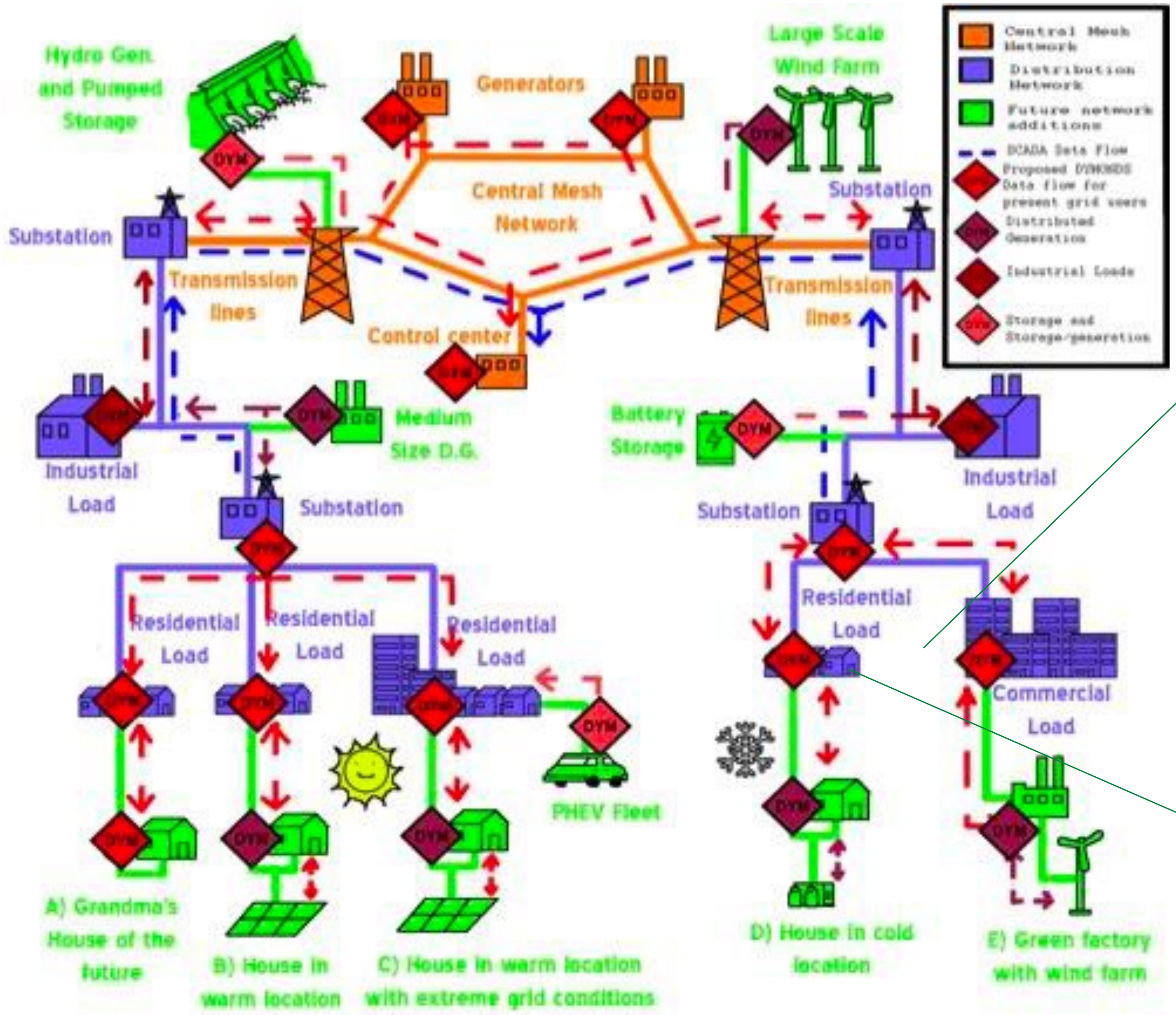
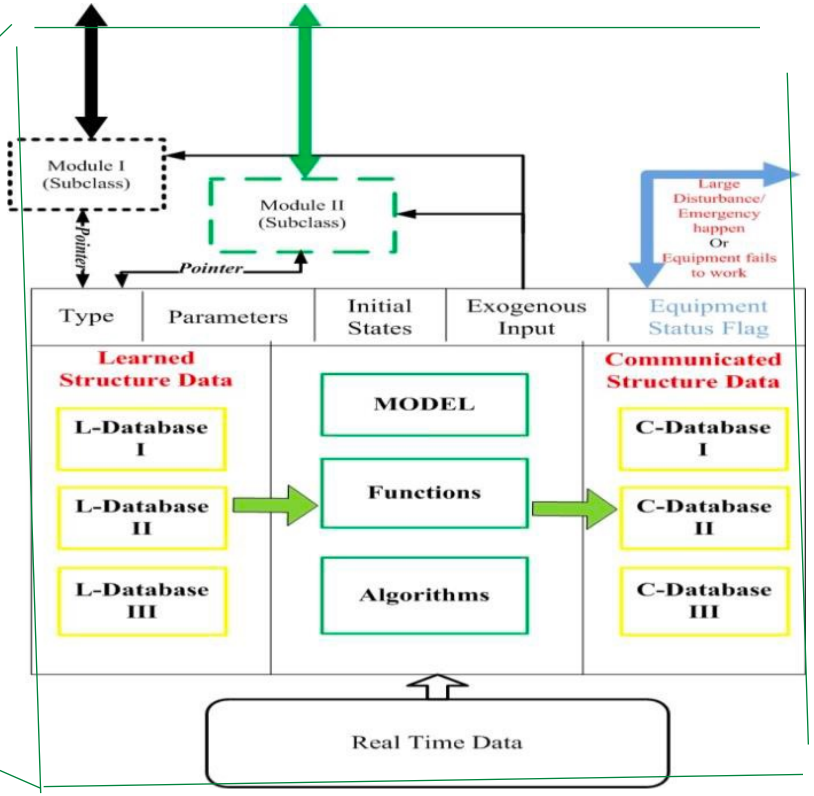
Cyber-secure Dynamic Monitoring and Decision Systems (DyMonDS); end-to-end outgrowth of today's SCADA

Marija Ilic, MIT and SmartGridz, Inc
ilic@mit.edu and milic@smartgridz.com

IEEE PES General Meeting, Orlando, FL, July 17-21, 2
Panel on ***Future electricity systems How to handle millions of power electronic-based devices and other emerging technologies***

Dynamic Monitoring and Decision Systems*

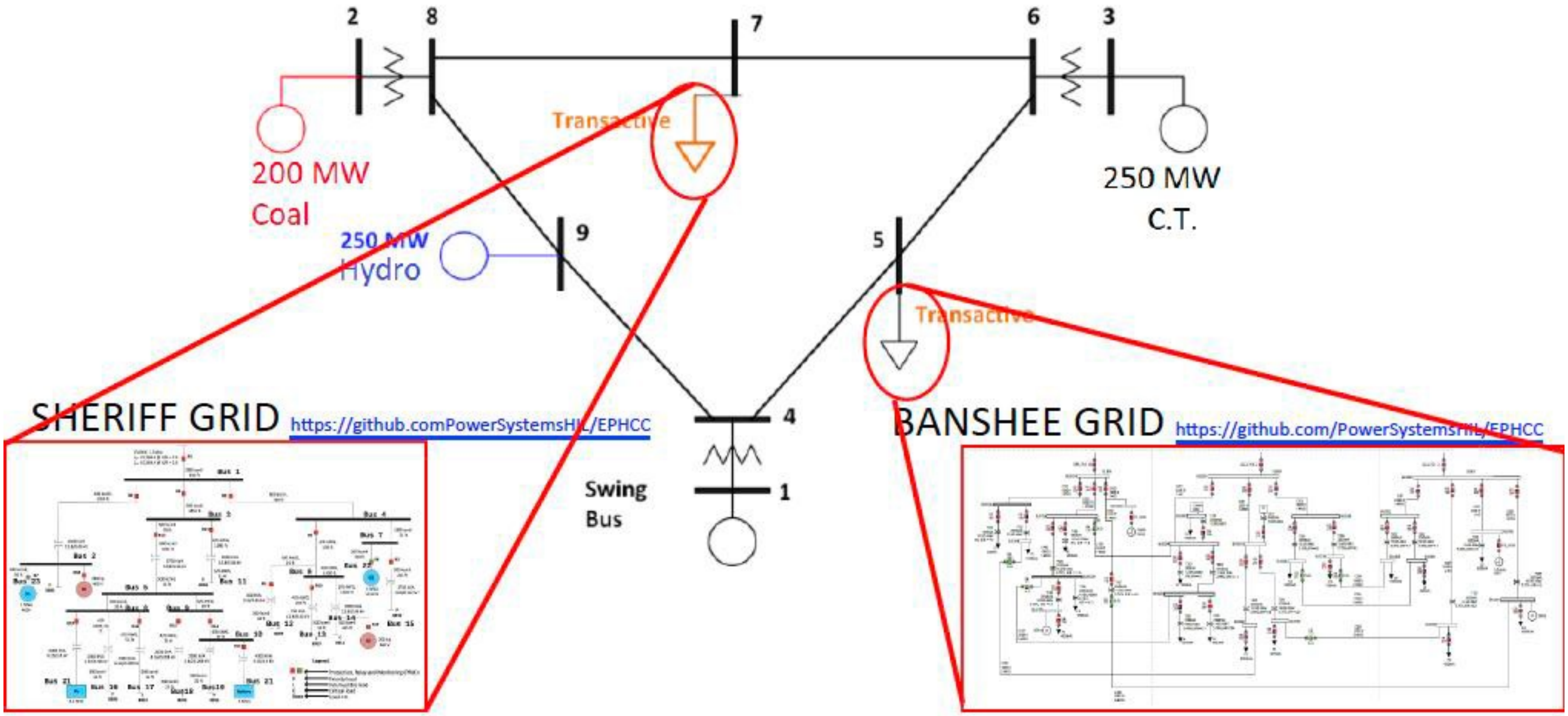




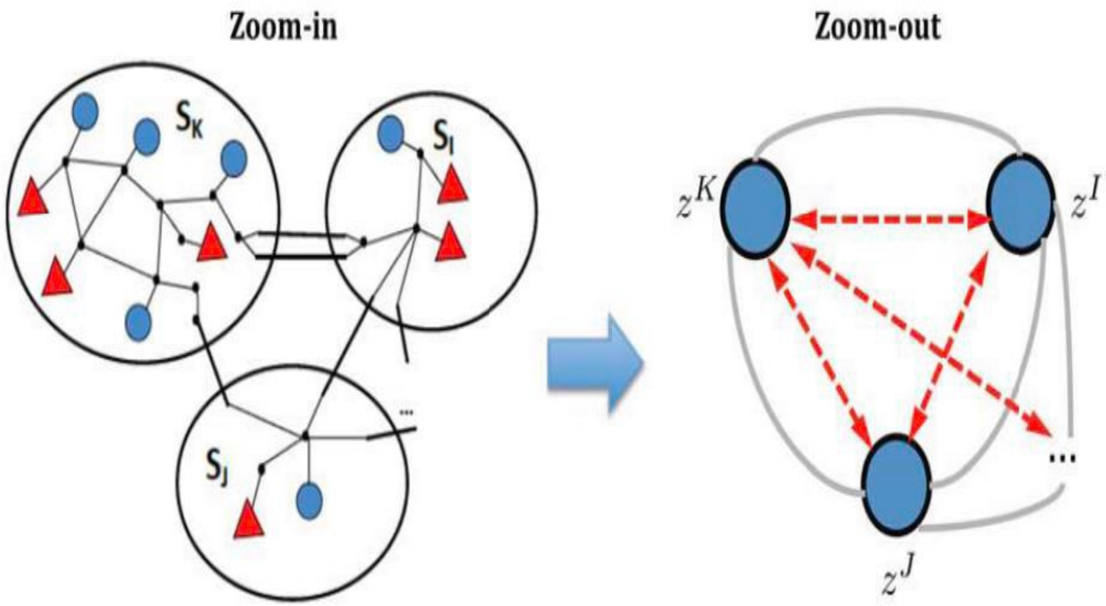
Local DyMonDS module

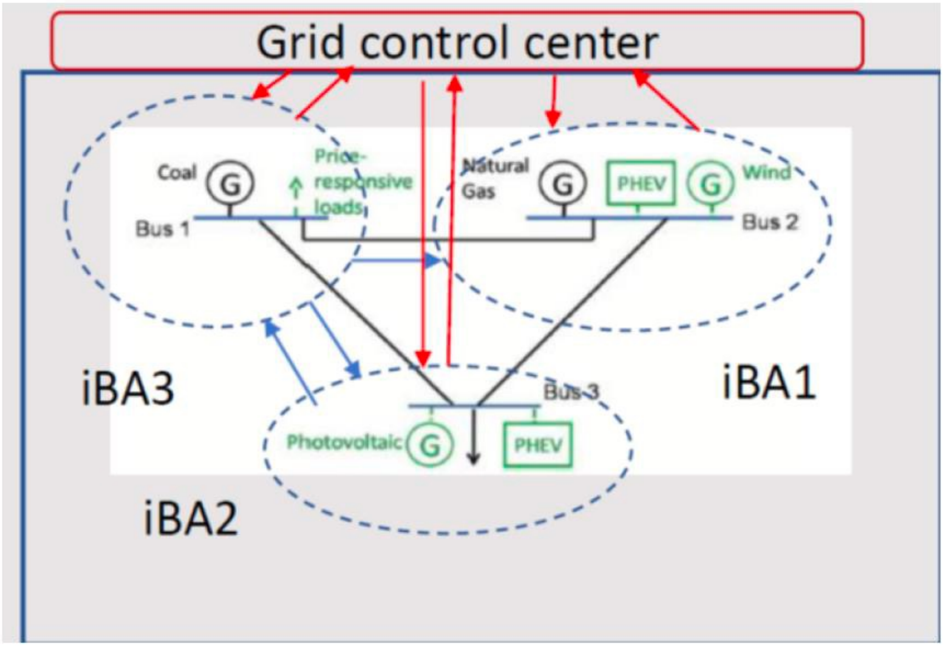
Ilić, M. D. (2010). Dynamic monitoring and decision systems for enabling sustainable energy services.Proceedings of the IEEE,99(1), 58-79.

Emerging multi-layered COMPLEX power systems

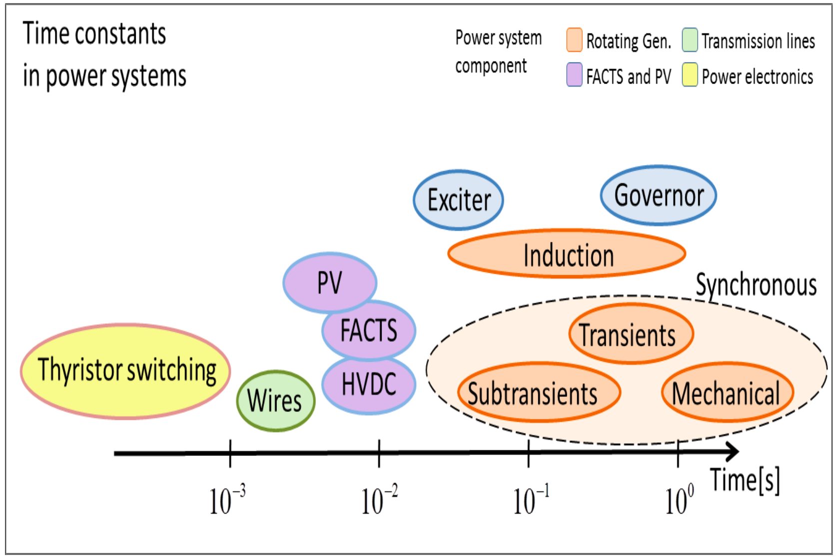


Intelligent Balancing Authorities (iBAs)





COMPLEX TIME SCALES New control equipment/new modeling and primary control challenge



❖Power system oscillations

▪Electro-mechanical—older problems (inter-area slow frequency oscillations; torsional oscillations)

▪Electromagnetic oscillations and their control-newer problems (caused by large generator faults in BPS; wind gusts/solar radiance in BPS/distribution/microgrids; SSCI—control induced, forced)

•Stability assessment

▪Extensive simulations-based studies; eigenvalue analysis

▪Hard to scale up, and find causes and effects

•Control for ensuring stable operations

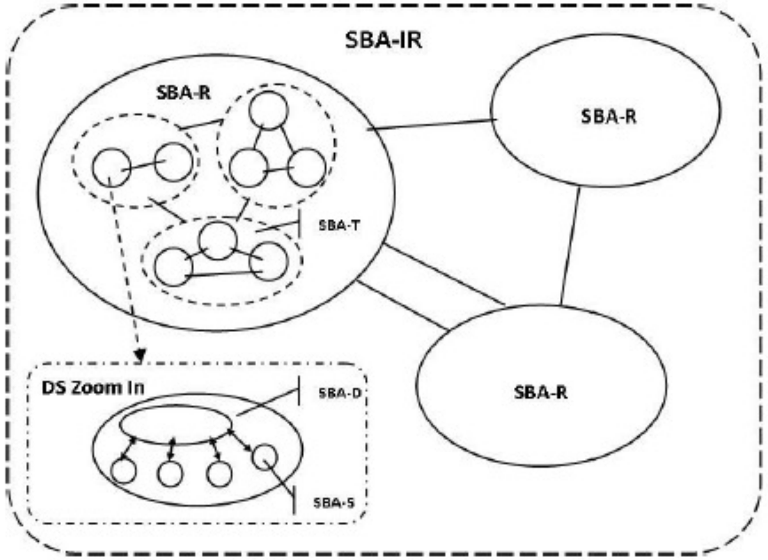
▪No systematic approaches to designing control for provably stable frequency/voltage regulation within reliability standards

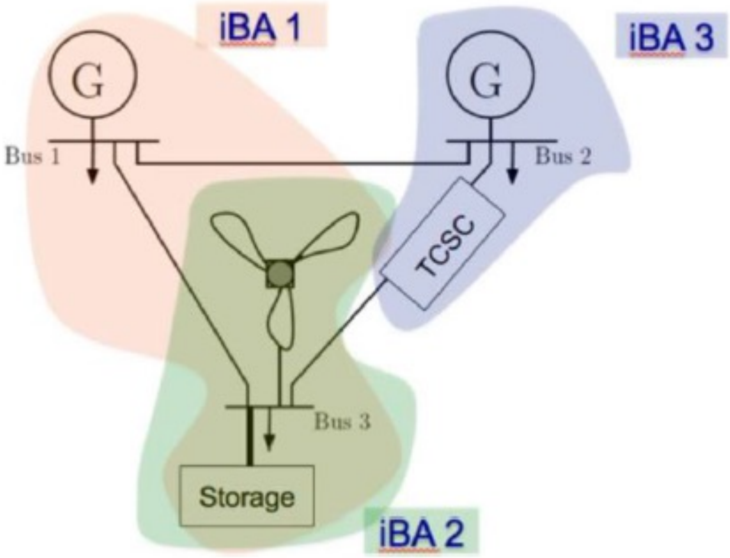
▪The worst case approach which does not ensure desired operations; various FFR, RFR system-specific requirements; UFLS

▪Sporadic R&D under different modeling assumptions

Is there a more general simple paradigm?

-general idea---rethink physical dynamics in terms of interaction variables



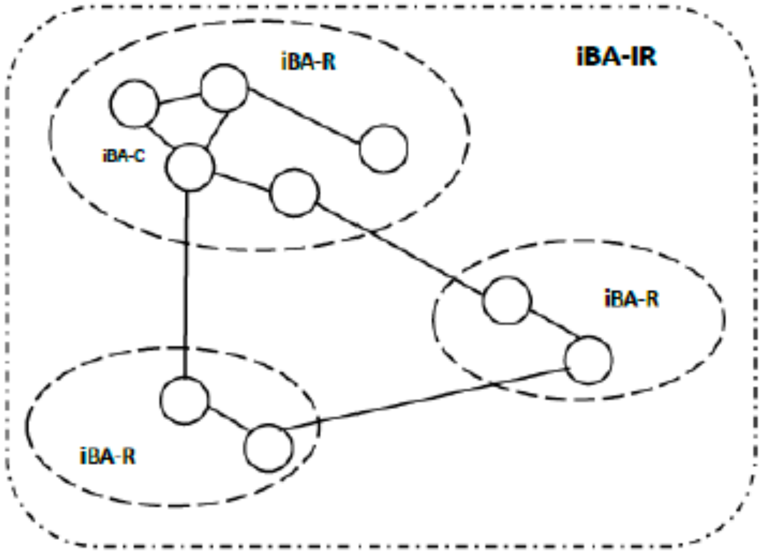


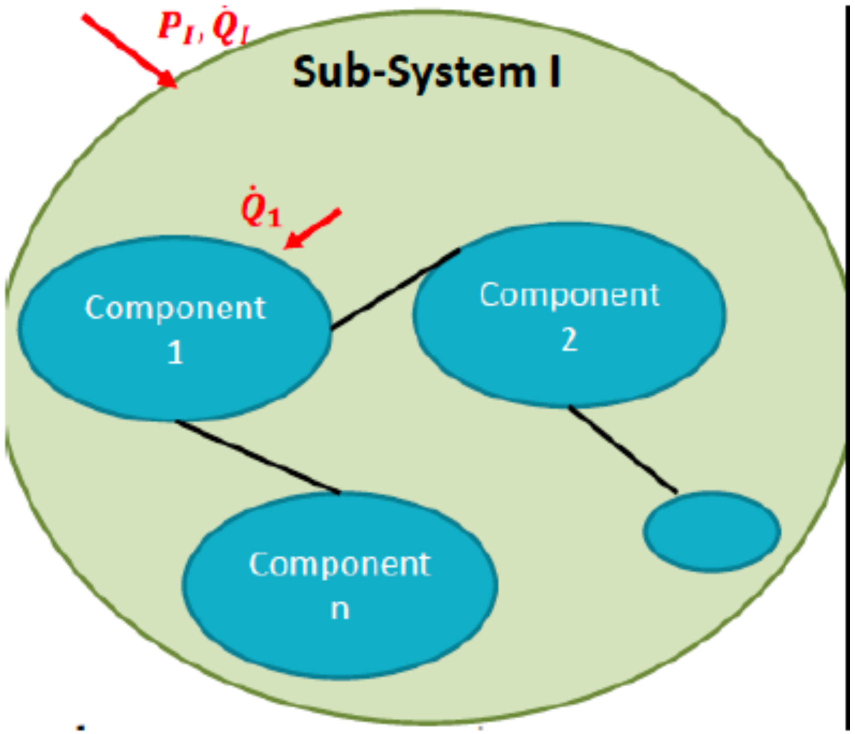
Note: SBAs renamed to iBAs (suggestion by a PSERC member some time ago)

Ilic, M., "Dynamic Monitoring and Decision Systems for Enabling Sustainable Energy Services", Network Engineering for Meeting the Energy and Environmental Dream, Scanning the Issue, Proc. of the IEEE,2011.

Baros, S., & Ilić, M. (2014, July). intelligent Balancing Authorities (iBAs) for transient stabilization of large power systems. In 2014 IEEE PES General Meeting| Conference & Exposition (pp. 1-5). IEEE.

Minimal information exchange



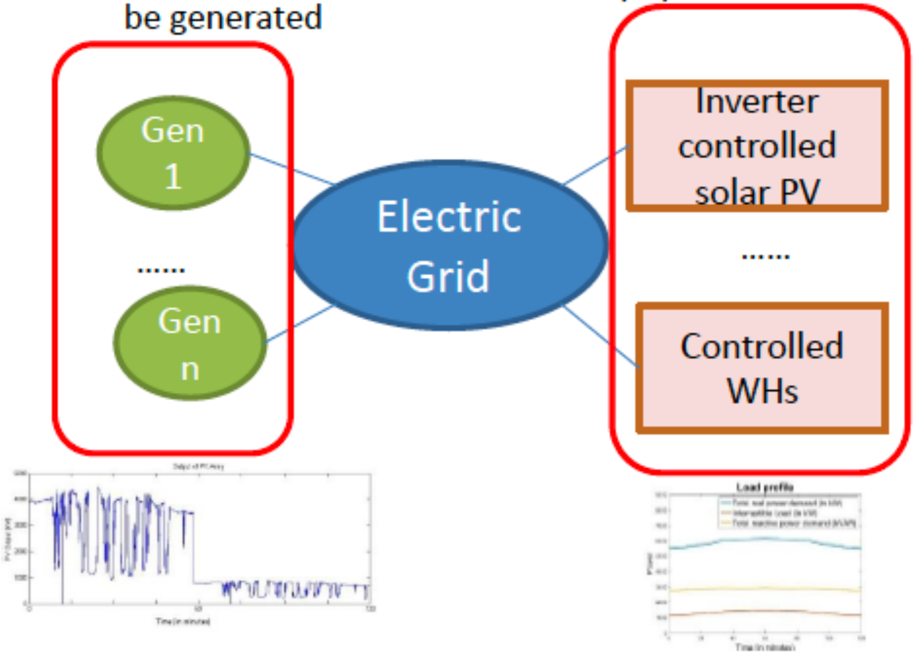


FROM TODAY'S BALANCING AUTORITIES TO NESTED INTELLIGENT (SMART) BALANCING AUTHORITIES (iBA)

Unifying energy-based dynamical modeling

Inertia used as a proxy to rates at which energy can be generated

Synthetic inertia used instead – non-physical



Fast varying generation

Slow varying demand

Heterogeneous end-end energy conversion processes modeling is becoming critical - inertia (or synthetic inertia) –ba approximated system analysis valid

Basis for energy as a state variable

Power conservation laws always hold at the interfaces of components a systems.

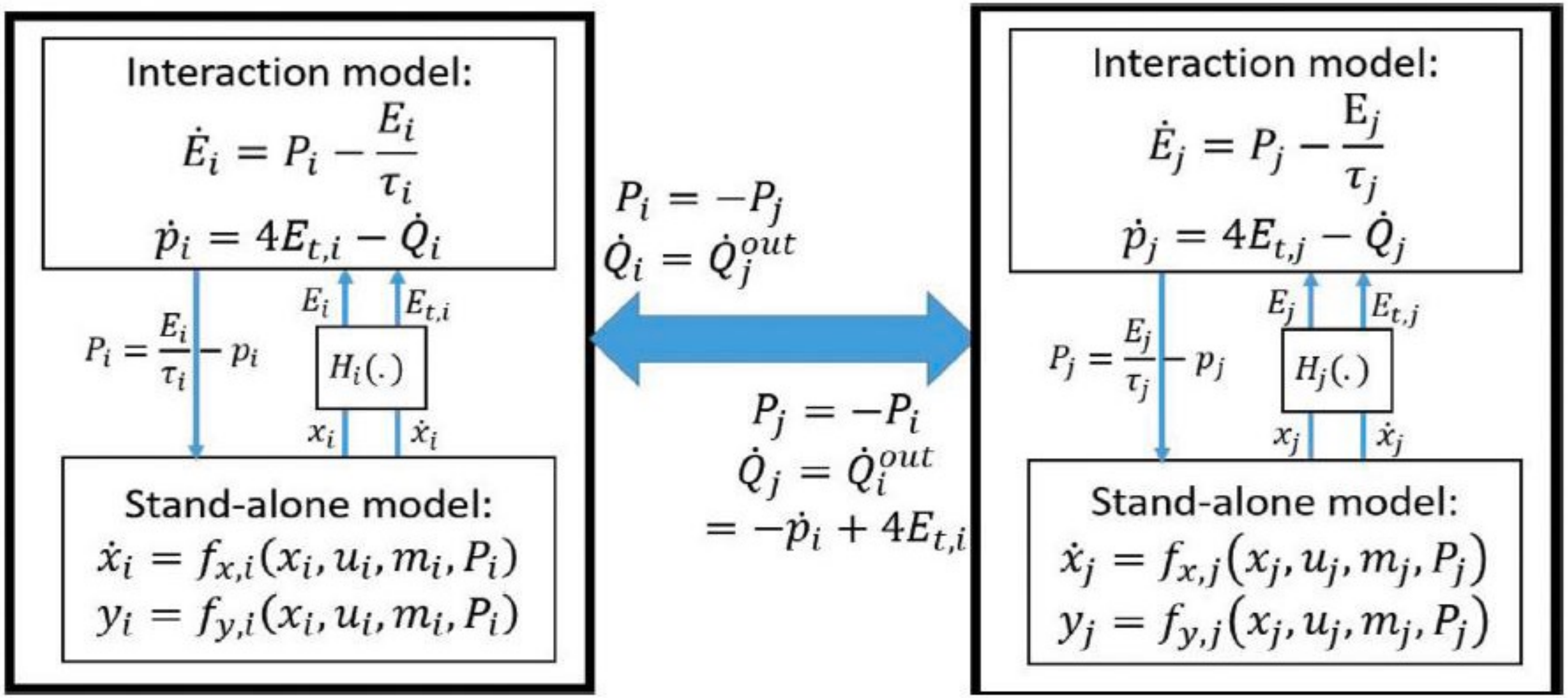
Basis for real power as an interface variable

Not all power produced can be delivered fundamentally due to mismatch in rates at which energy conversion processes of connected components tak thermal losses ought to be ca

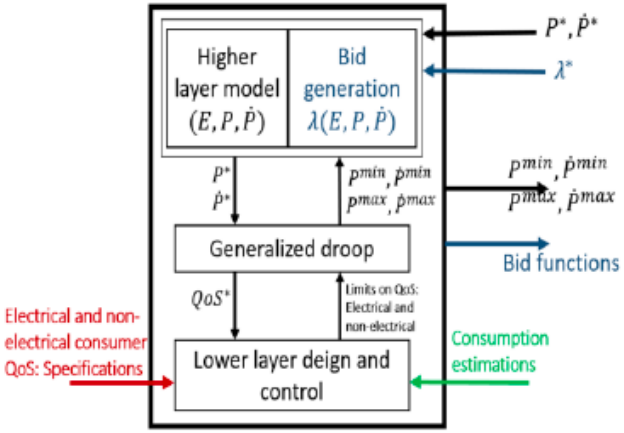
Basis for reactive power as an interface variable

Ilić, M. D., & Jaddivada, R. (2018). Multi-layered interactive energy space modeling for near-optimal electrification of terrestrial, shipboard and aircraft systems. Annual Reviews in Control,45, 52-75.

Multi-layered interactive model

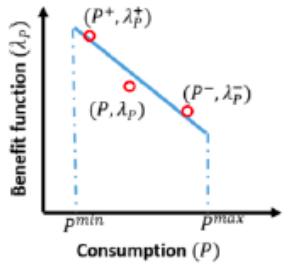


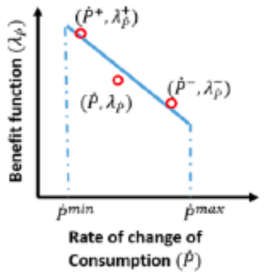
Load specification

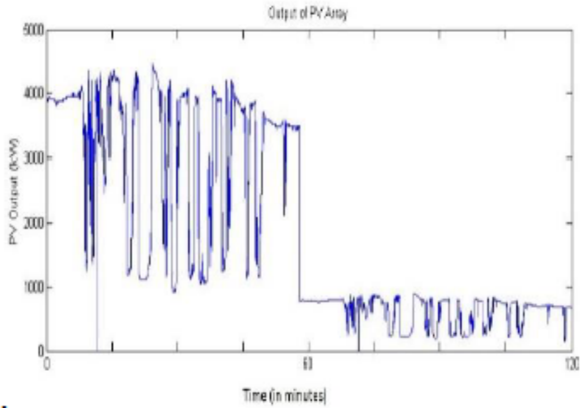


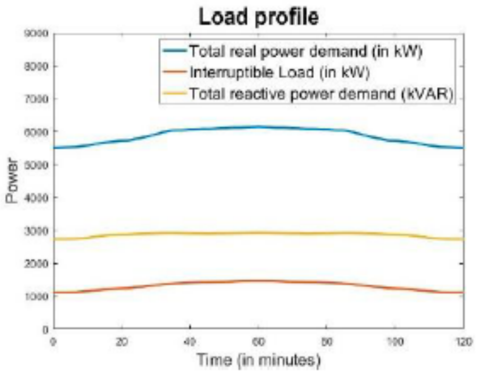
Type of Load	Minimum Loading				Maximum Loading			
	Real Power		Reactive Power		Real Power		Reactive Power	
	Absolute Demand (in MW)	% of total Demand	Absolute Demand (in MW)	% of total Demand	Absolute Demand (in MW)	% of total Demand	Absolute Demand (in MW)	% of total Demand
Priority	0.99	36.14	0.44	57.33	3.90	50.39	1.93	60.25
Critical	1.01	37.15	0.21	27.79	1.18	15.30	0.81	25.21
Interruptible	0.73	26.70	0.11	14.88	2.65	34.31	0.47	14.54
Total	2.73		0.76		7.73		3.21	

Input-output in energy space









Economic and physical characterization

Example of IntVar for PV module

Energy Space Model:

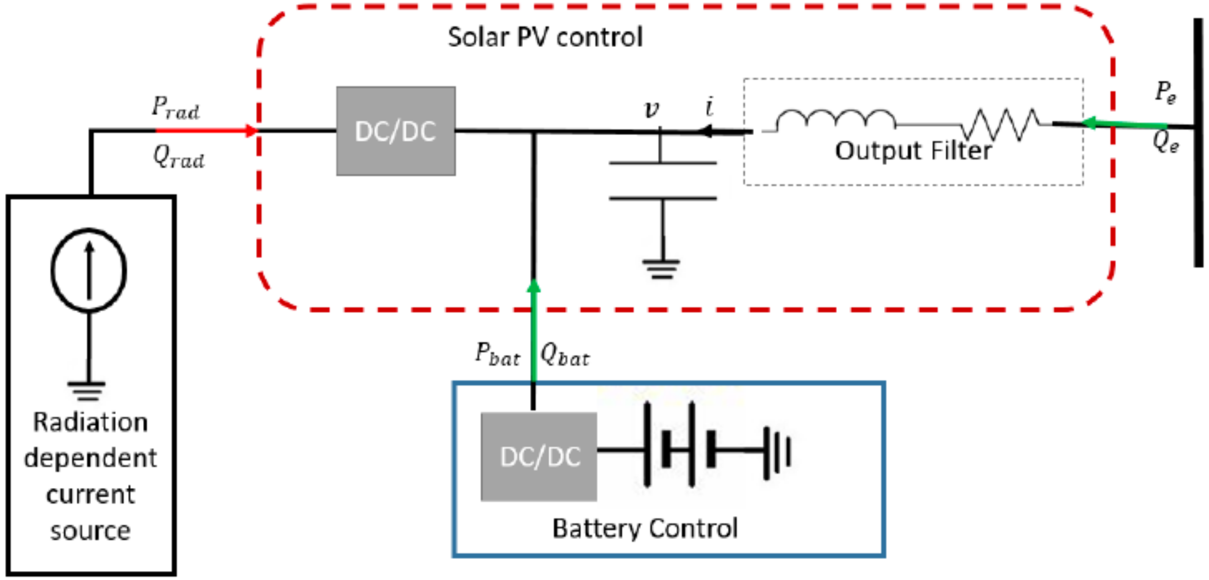
$$\dot{E}(t) = P_{rad}(t) + P_{bat}(t) + P_e(t) - \frac{E(t)}{\tau} = p(t)$$
$$\dot{p}(t) = 4E_t(t) - \dot{Q}_{rad}(t) - \dot{Q}_{bat}(t) - \dot{Q}_e(t)$$

Here, $E(t) = \frac{1}{2}Li(t)^2 + \frac{1}{2}Cv(t)^2$

- The power electronics switch control of battery can be so designed that would ensure

$$P_{bat}(t) = -P_e[n] + P[n] - K_i^P\left(i_F(t) - i_F^{ref}[n]\right) - K_V^P\left(V(t) - V^{ref}[n]\right)$$
$$Q_{bat}(t) = -Q_e[n] + Q[n] - K_i^P\left(i_F(t) - i_F^{ref}[n]\right) - K_V^P\left(V(t) - V^{ref}[n]\right)$$

Coupled Droop: $\alpha\Delta P[n] + \beta\Delta Q[n] = \Delta V[n]$



Over much longer time scale identified by sample number k, it is possible to obtain the following relation (assuming converter efficiencies are all 100%)

PV Energy-conversion Droop Relation:

$$\Delta P[k] + \Delta P^{Bat}[k] = \Delta P^{rad}[k]$$

DER Energy Conversion Droop Relation: $\Delta P[k] = \sigma\Delta W[k]$

Unifying properties of intVars

Property 1:[Ilic,Liu]

Interaction variables are function of local variable alone

$$z_i^{r,out} = \begin{bmatrix} \int_0^t P_i^{r,out} dt \\ Q_i^{r,out} \end{bmatrix} = \begin{bmatrix} E_i + \int_0^t \frac{E_i}{\tau_i} dt \\ \int_0^t 4E_{t,i} dt - p_i \end{bmatrix} = f(x, \dot{x})$$

Property 2: [Ilic,Liu]

Interaction variable of a component i is a variable $z_i^{r,out}$ that satisfies

$$z_i^{r,out}(t) = constant$$

when all interconnections among subsystems are removed and the system is free of disturbances

$$\dot{z}_i^{r,out} = L_z^{-1} \dot{z}_i^{r,in} = 0$$

No linearization!

No decoupling!

The same definition

Property 3: (State of art in power systems)

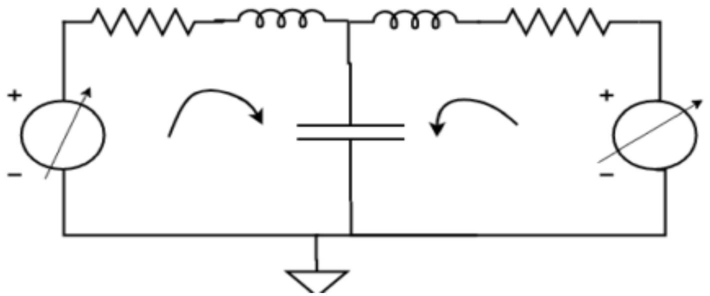
Dynamics of reactive power can be neglected when voltage is not changing

Generalized reactive power:

$$\dot{Q}_i^{r,in} = v_i \frac{di_i}{dt} - \frac{dv_i}{dt} i_i = \dot{P}_i^{r,in}$$

Property 4: (Circulating currents)

Circulating currents are indicative of non-zero reactive power dynamics



intVars basis for secure DyMonDS

- IntVar is a function of its own internal state variables only
- intVar rate of change is zero when disconnected from the rest of the system

- Basis for distributed monitoring and cooperative control
- Basis for computing based on internal variable only (cyber-secure)
- Area control error (ACE) sub-case of intVar*

The basic idea: Compute technology-specific intVar using internal, safe measurements; compare with the intVar measured**

**Pending MIT patent on Cyber –secure DyMonDS
Application no 63/225,873 , filed July 2021