Interaction variables–based modeling and simulations of energy dynamics*

©Marija Ilic   ilic@mit.edu

11th MSCPES Workshop

May 9, 2023

San Antonio, Texas

*Based on the upcoming chapter Marija Ilic, *Interaction Variables-based Modelling and Control of Energy Dynamics, in Springer Nature,* Women in Power:Research and Development Advances in Electric Power Systems, Editors: Jill S. Tietjen, Marija D. Ilic, Lina Bertling Tjernberg, Noel N. Schulz ,June 2023, https://link.springer.com/book/9783031297236

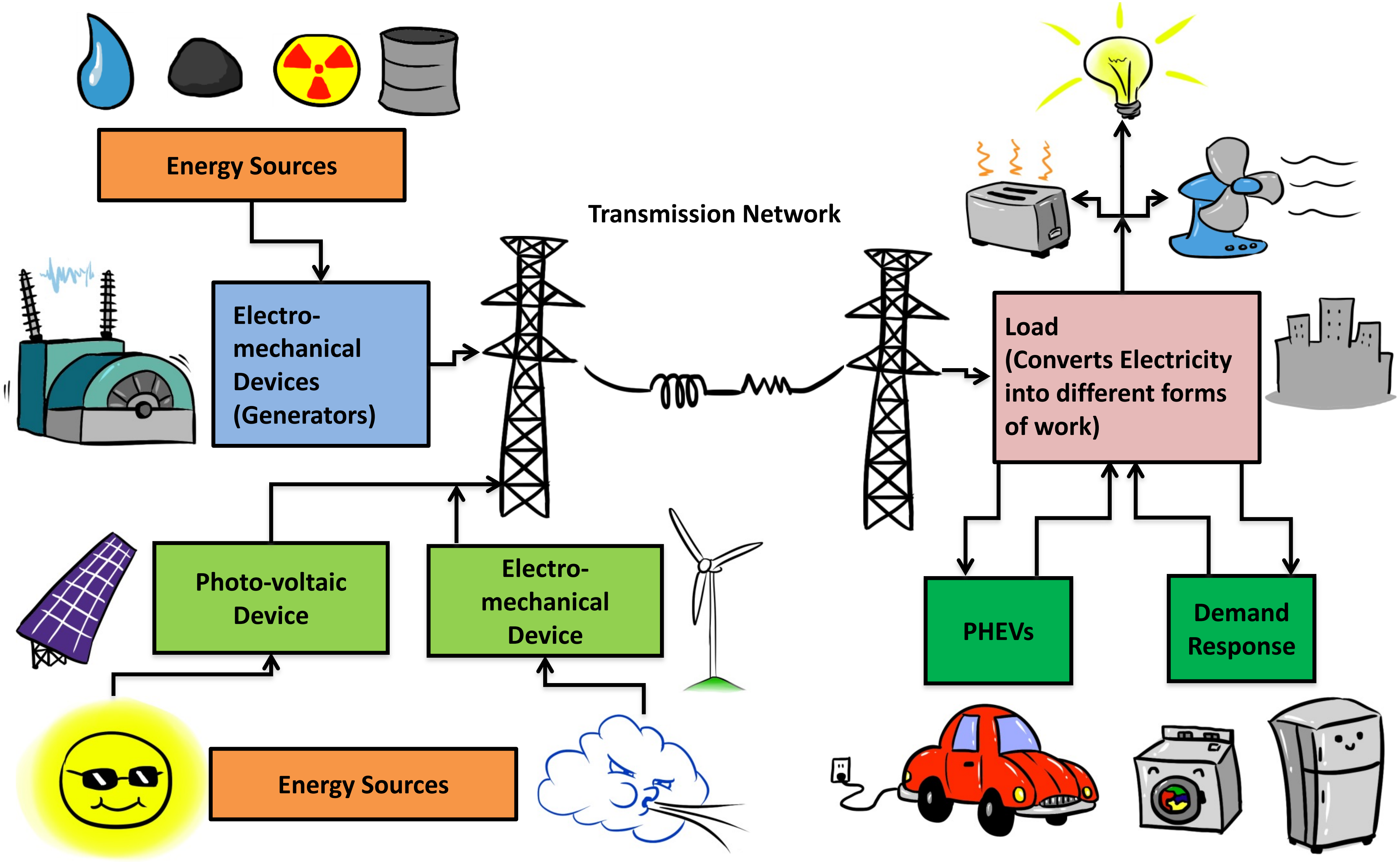
EESG @MIT

Outline

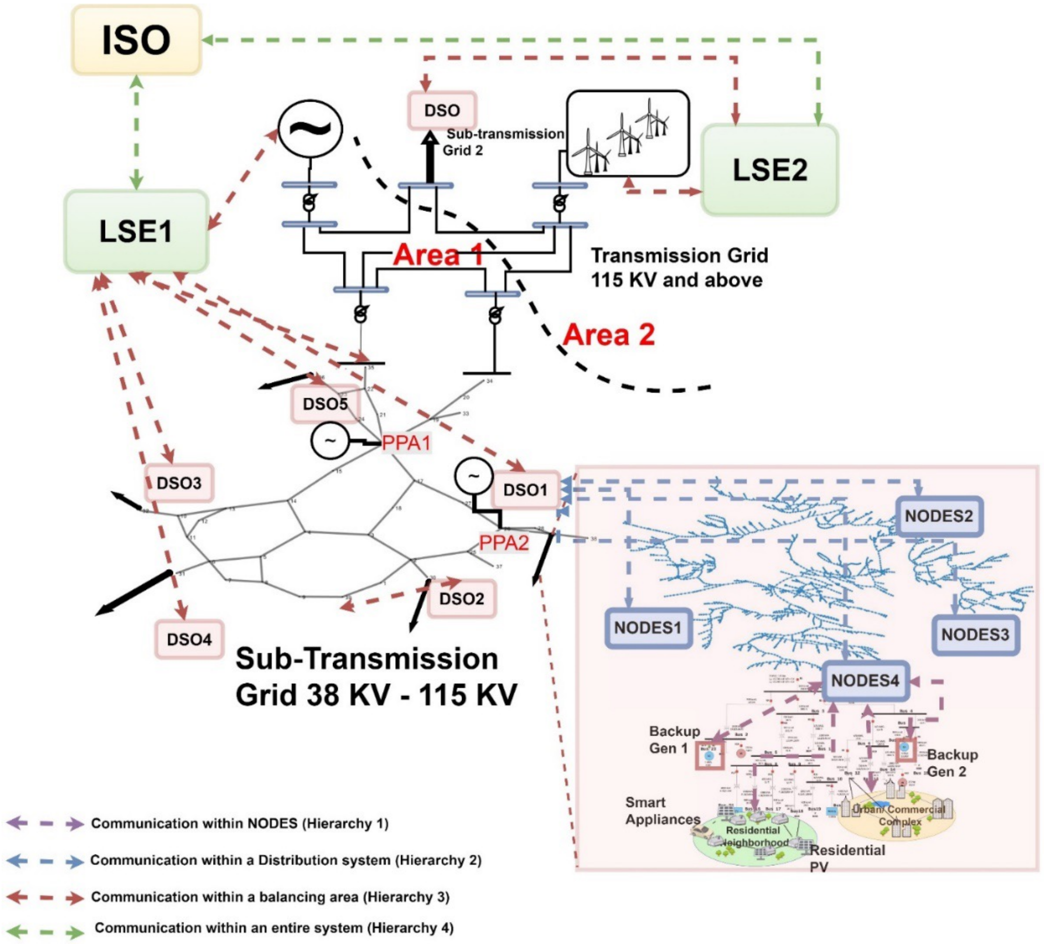
- Spatial, temporal complexity, new diverse technologies
- Emerging fundamental modeling, simulation and control needs
- **Challenges** (new multi-layered SCADA-DyMonDS; minimal information exchange for managing temporal and spatial complexity)
- **Opportunities**: Systematic interaction variables- based energy dynamics; unified energy dynamics
  - Early concept of interaction variables
  - General concept (no P-Q decoupling, no linearization)
- Interactive optimization problem formulation in energy space
- Digital twin which might work

EESG @MIT

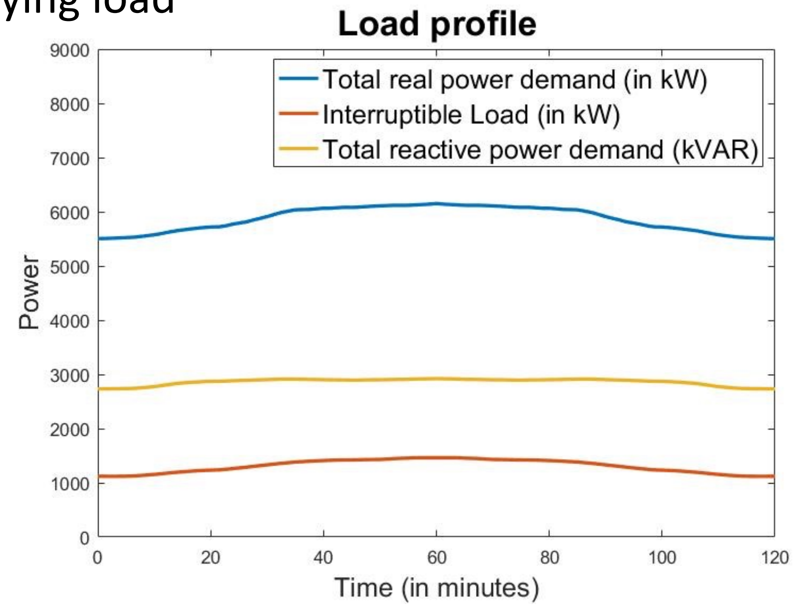
Future Power Systems-Diverse Physics



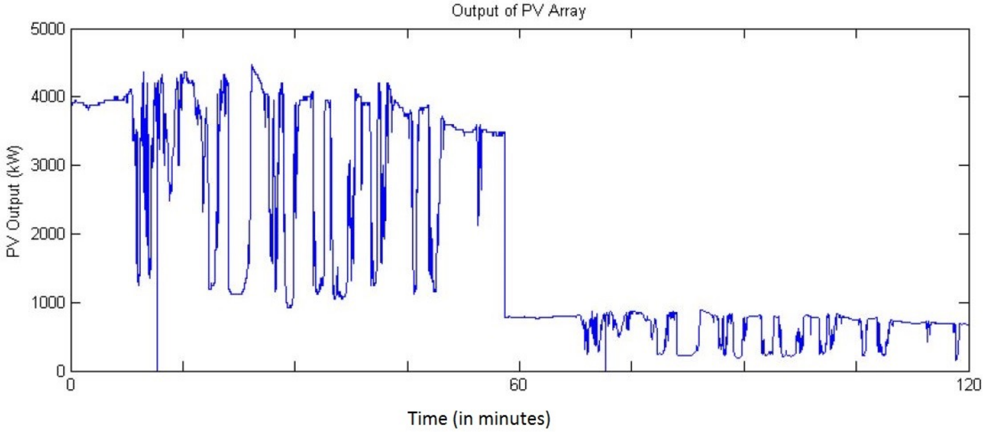
Temporal and spatial interactions across stakeholders



Slow-varying load



New high frequency disturbances from renewables



Challenges—It may not work! Emerging dynamical problems

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

▪Sporadic R&D under different modeling assumptions

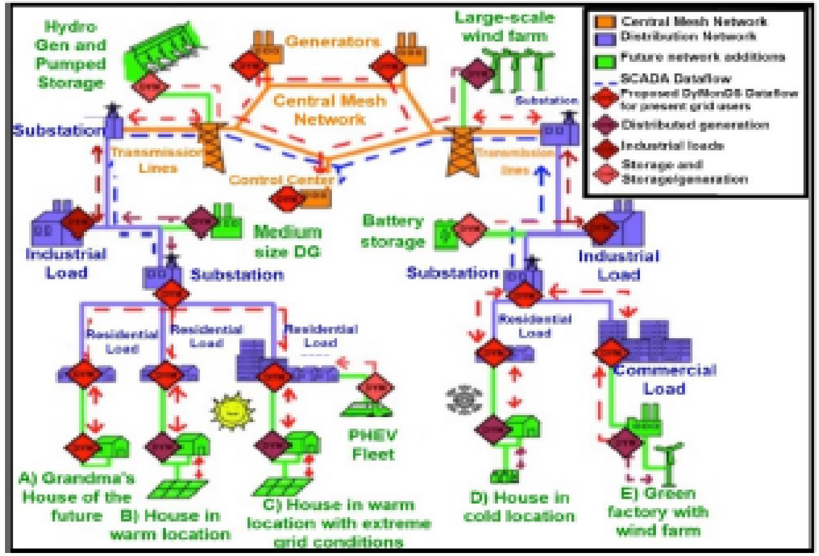
- **Sensing, communications, control technologies mature**
- **Missing piece of the puzzle: Integration framework for aligning end users, resources and governance system**
- **Multi-layered interactive data-enabled (Internet-like) protocols**

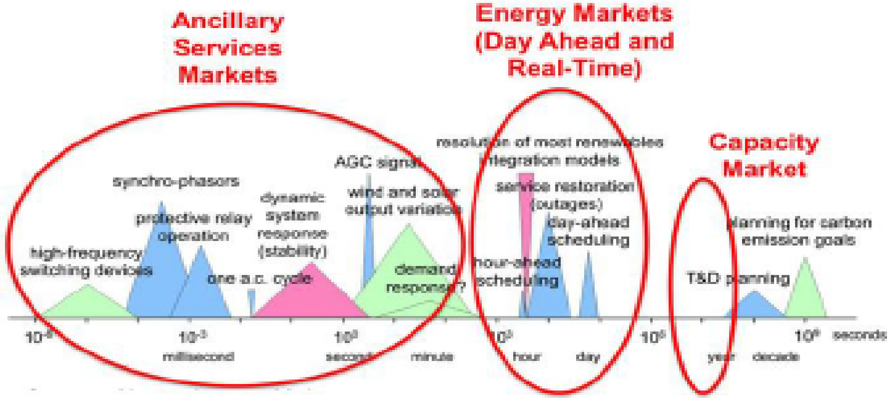
-- Highly distributed decision makers

--Minimal coordination of interactions

Ilic, M, A roadmap for technology deployment and its utilization at value for the changing electric energy industry, MIT EESG WP2020-2, April 2020.

Roadblocks to integration into BPS





Missing spatial and temporal signals in

Operations:
Power and rate of change of power

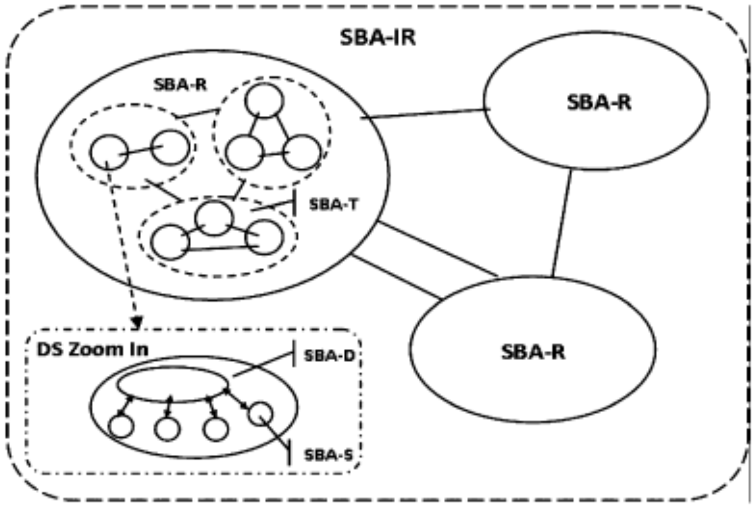
Markets:
Prices at consumer locations for power and its rate of change and rate of change of power

Need for next generation SCADA (architectures)

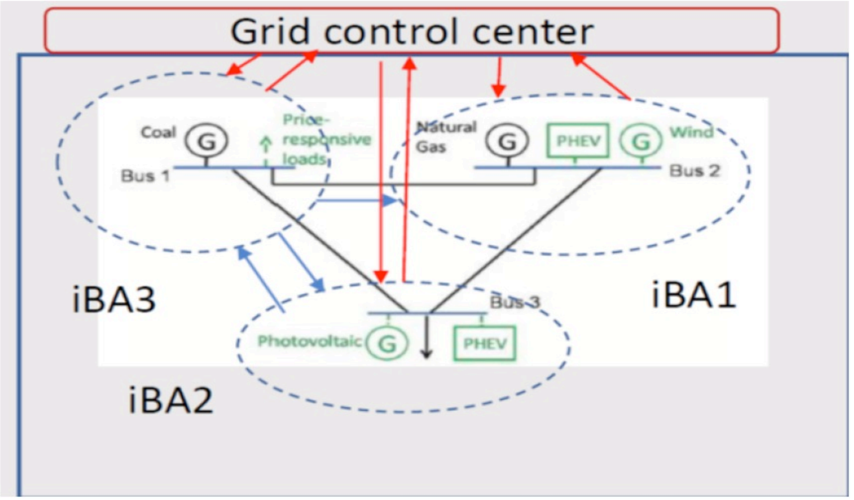
``The systems most fitted for a purpose are those where the number of bits transferred between sub-systems in achieving this purpose is minimized". (David Hirst, UK consultant, Aug 2016)

Emerging fundamental needs

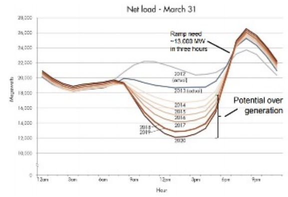
- New architectures (nested, multi-layered)
- Operations and planning – data-enabled interactive decisions Multiple heterogeneous decision makers (physics, sub-objectives);
- Multiple granularity, temporal and spatial; intermittent
- Need for decision tools at different system layers and for their interactions over time and geography
- Lack of well-defined protocols for supporting this process
- **Lack of provable software algorithms**



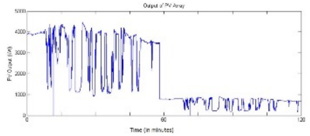
Intelligent Balancing Authorities (iBAs)



Temporal inter-twining

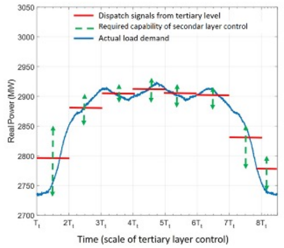


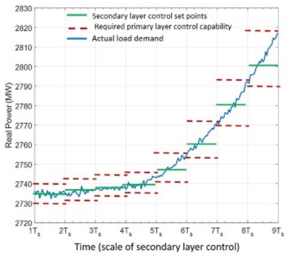
Aggregate effect of solar



Local solar

Hard to predict inputs





Nonzero mean effects

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

CPES challenge—enablers of stable clean services

- The need for enhanced end-to-end SCADA for managing interactions across DERs/microgrids-DSOs-TSOs-ISOs ; future SCADA protocols ?
- Multi-layered modeling of interactions between the distributed components in terms of common variables (understood by the engineers, economists, regulators)?
- **The fundamental role of data-enabled software in making components and system performance ``better”**
- **Digital twin that might work?**

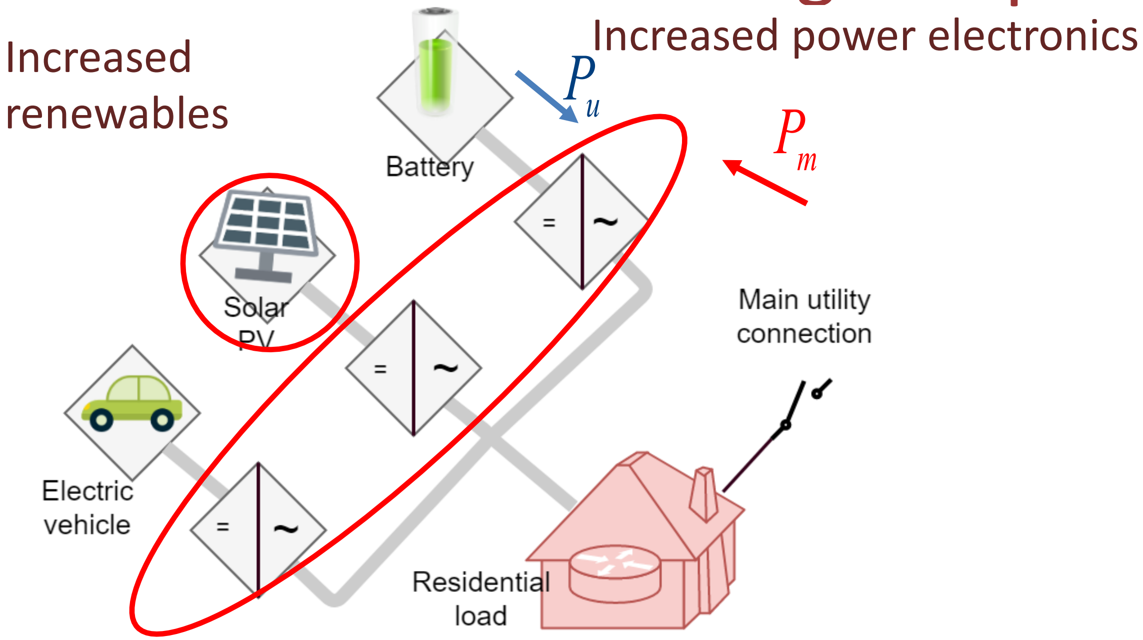
EESG @MIT

Typical problems when attempting to integrate smaller-scale MV/LV stakeholders in bulk power systems and electricity markets

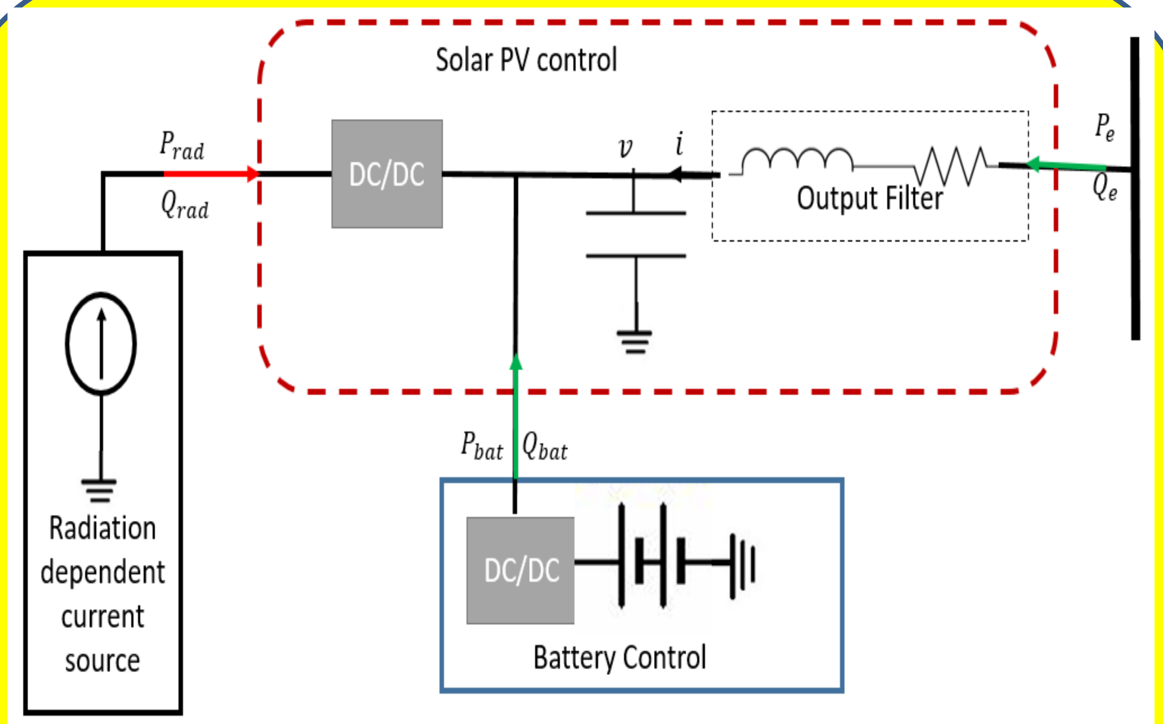
- Lack of accurate information about the grids and stakeholders' models
- Numerical problems when combining radial distribution systems software into software which must model their meshed system interactions (typically needed when connecting and disconnecting for economic and reliability reasons)
- Representing interactive inter-temporal effects; instability concerns
- **The basic challenge: Establish an interactive co-simulator which enables communications at the interfaces between models and software of different modeling granularity; ultimately a digital twin**

Basic R&D control challenge:

Overcoming complexity of modeling and control

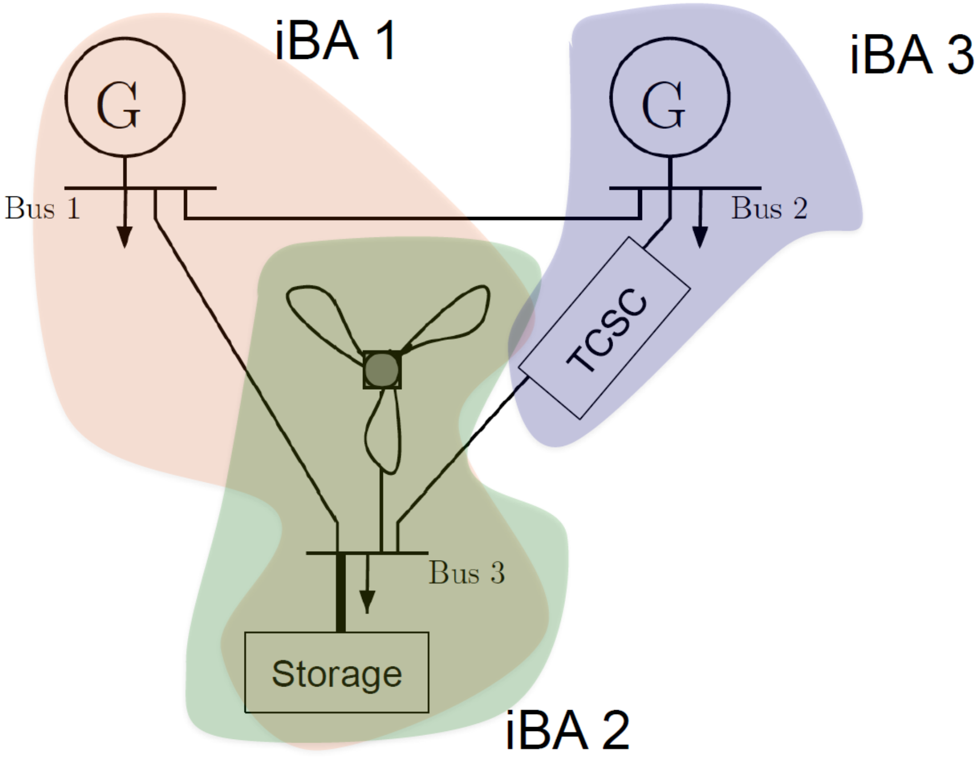


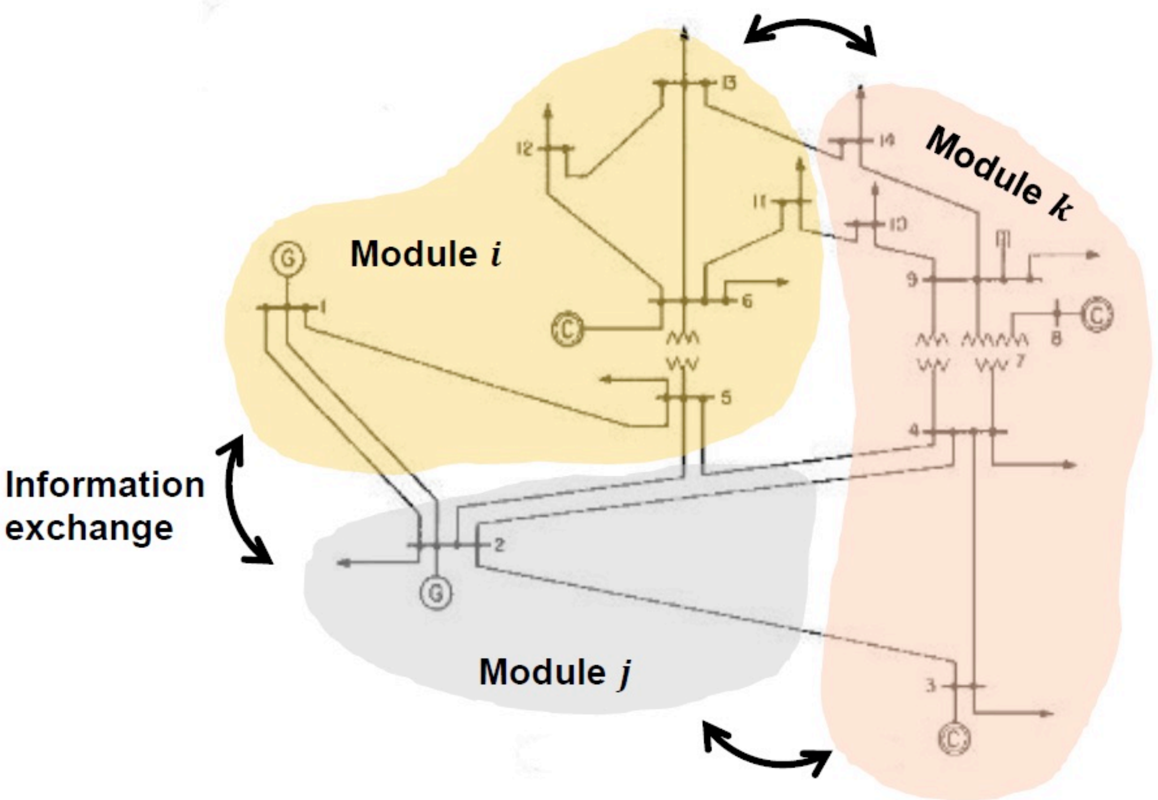
Crux of the problem: Present controls are designed for $P_m(t)$ without considering its dynamical effects



Model of solar PV droop? Starting from physics!!!

Opportunities: Int variables-based information exchange

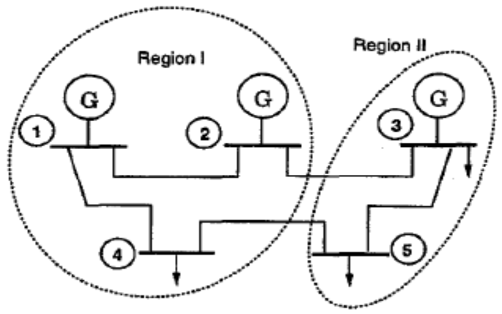




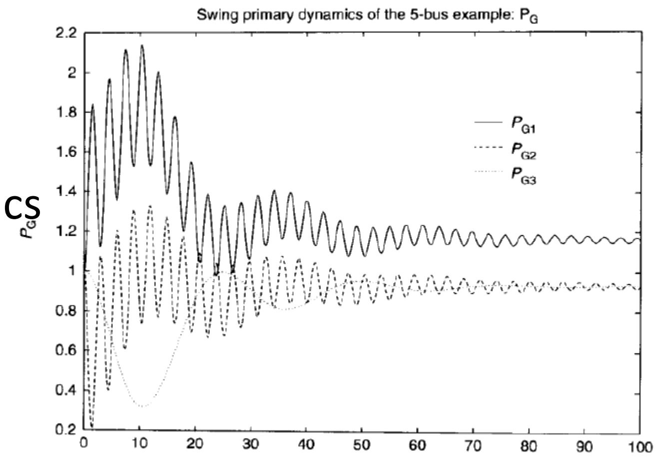
EESG @MIT

Inter-area dynamics- interaction variable

The first concept using linearized decoupled real power –frequency dynamical model



Local/internal dynamics



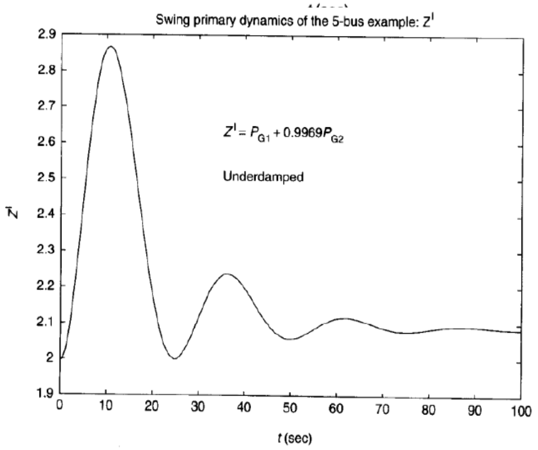
DEFINITION The interarea variables $z(t)$ are variables that satisfy

$$z(t) = \text{const} \qquad (6.121)$$

when all interconnections among the subsystems S^i, $i = \mathrm{I}, \ldots, R$ are removed, and the system is free of disturbances.

$$z^i(t) = P^i x^i(t), \qquad i = \mathrm{I}, \mathrm{II}, \cdots \qquad (6.122)$$

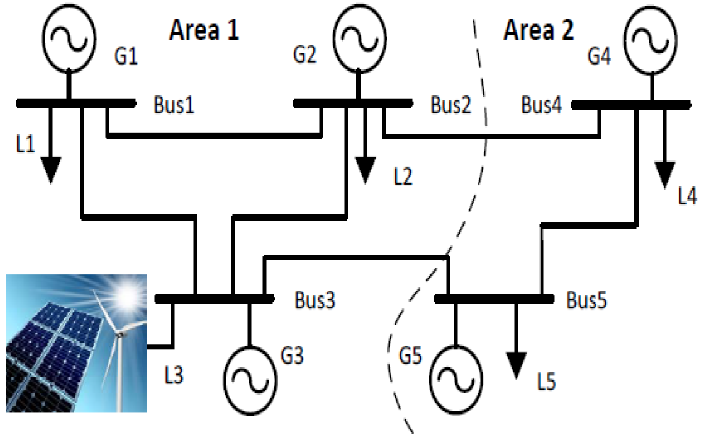
$$z^i(t) = p^i P^i_G \qquad (6.131)$$

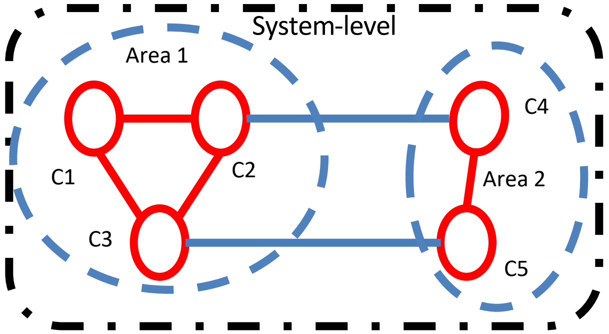


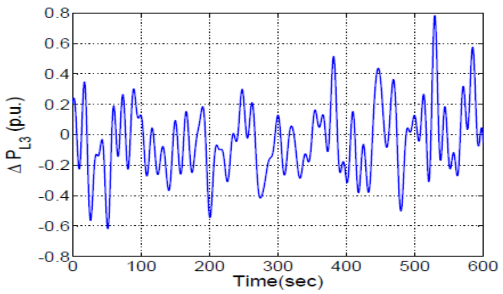
Ilic, Marija, X. Liu, B. Eidson, C. Vialas, and Michael Athans. "A structure-based modeling and control of electric power systems." *Automatica* 33, no. 4 (1997): 515-531.

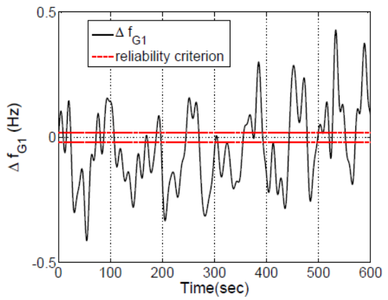
EESG @MIT

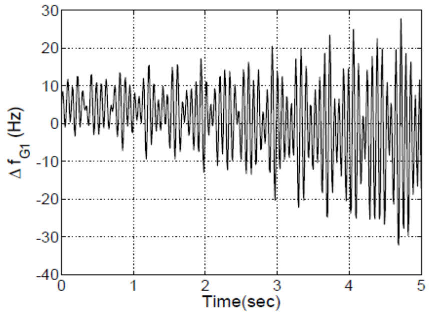
Need for coordinated frequency control with intermittent disturbances





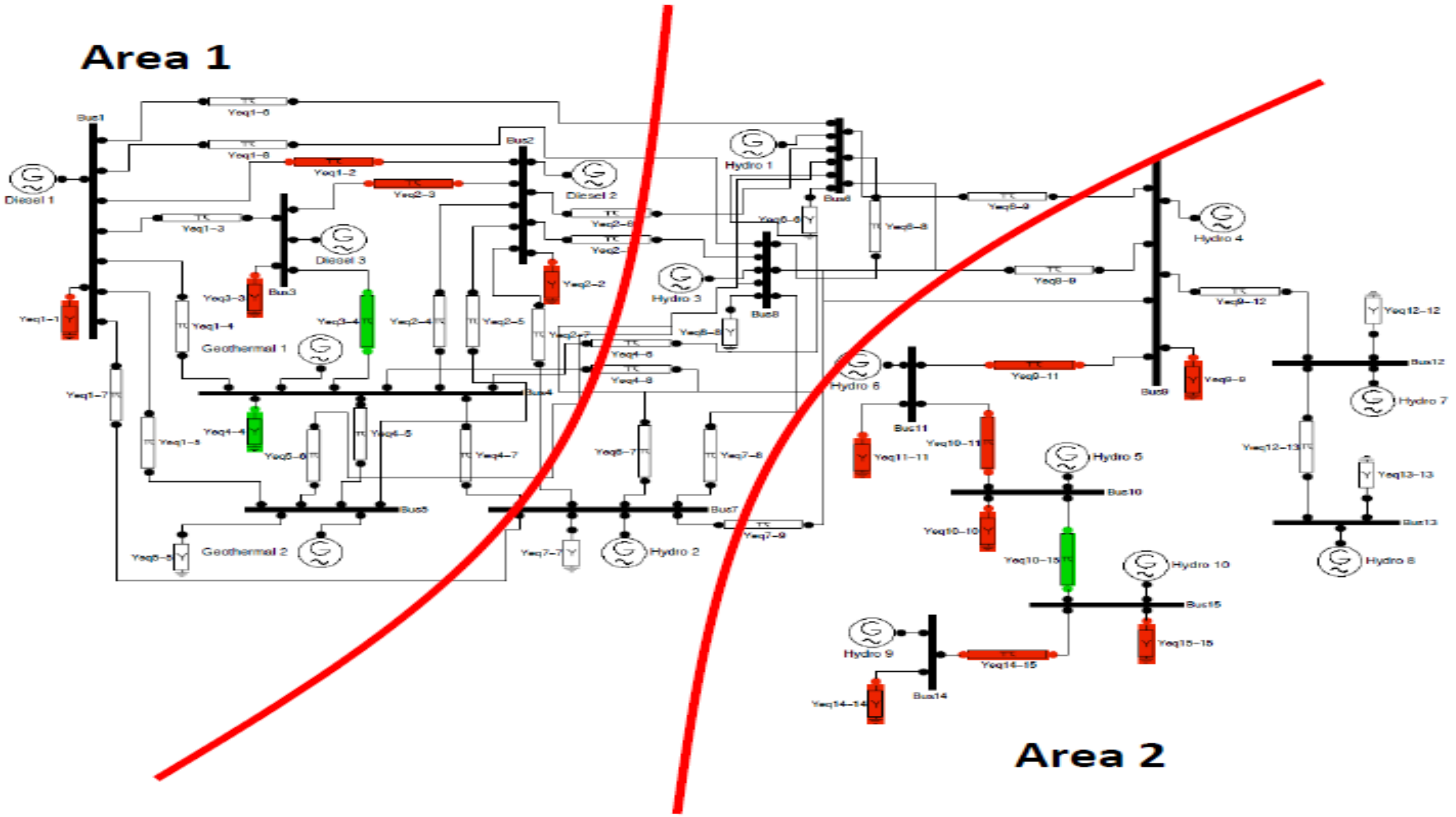






CONTINUOUS POWER FLUCTUATIONS AND OPERATING PROBLEMS (POOR FREQUENCY QUALITY, INSTABILITIES)

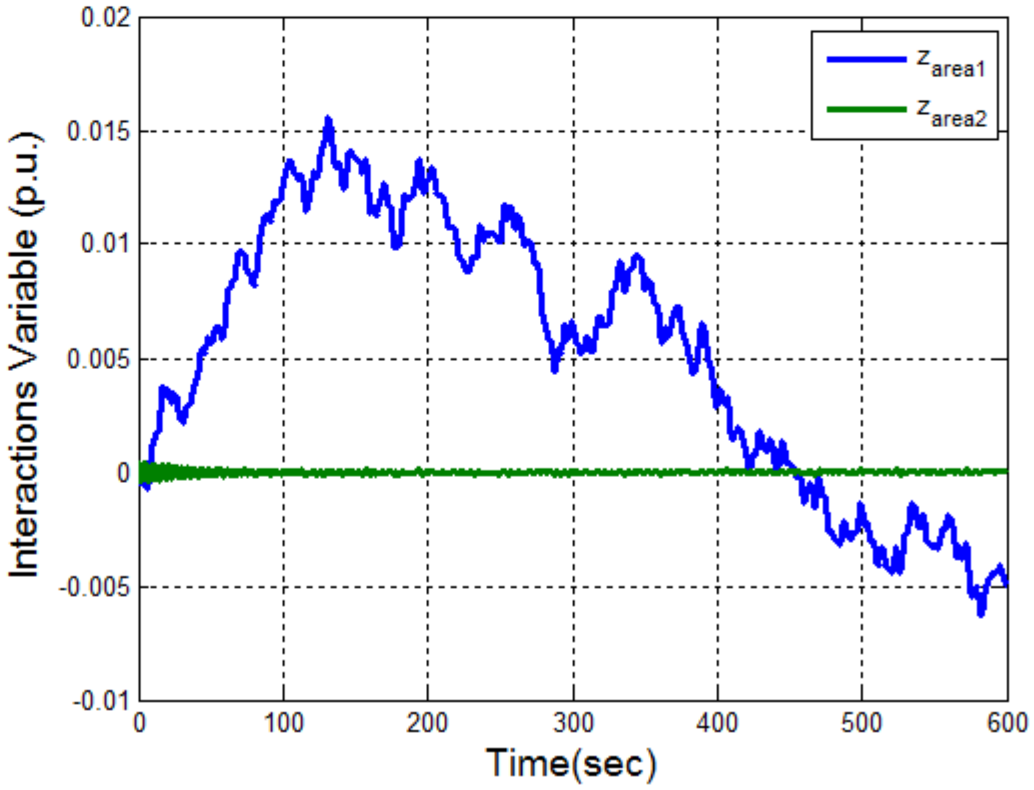
Dynamics of interaction variables between the areas—Sao Miguel

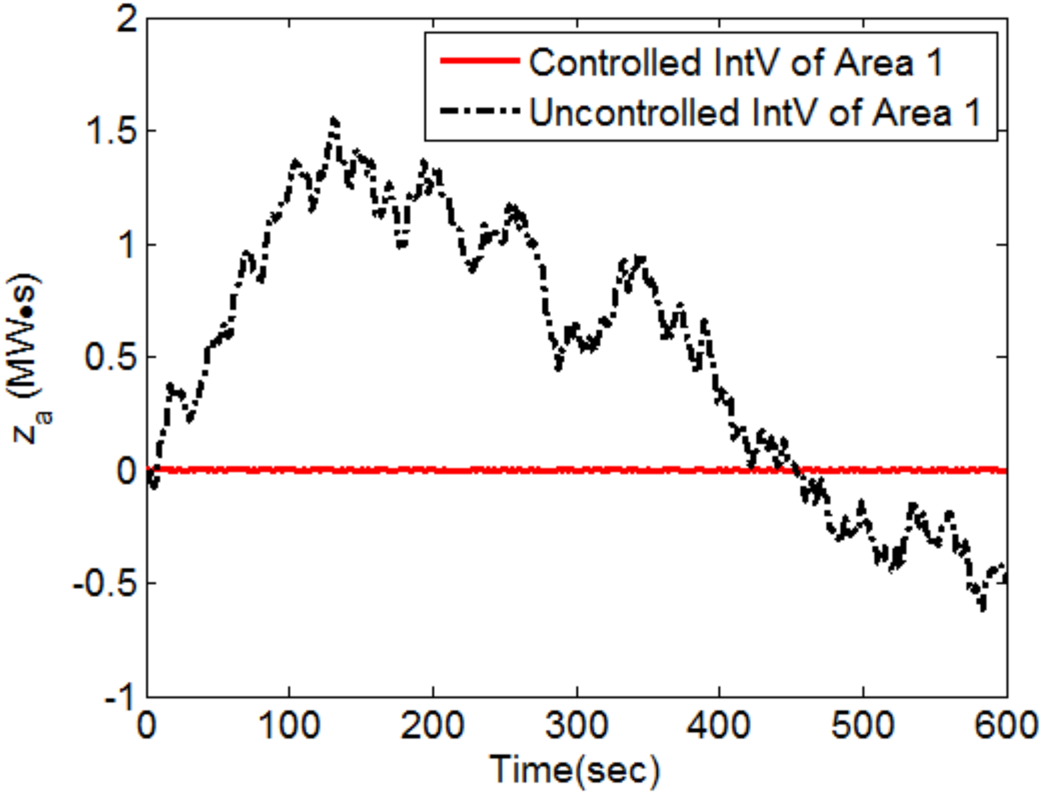


[2] M. Ilic "The Tale of Two Green Islands in the Azores Archipelago," Chapter 2 of Engineering IT-Enabled Sustainable Electricity Services : The Tale of Two Low-Cost Green Azores Islands.

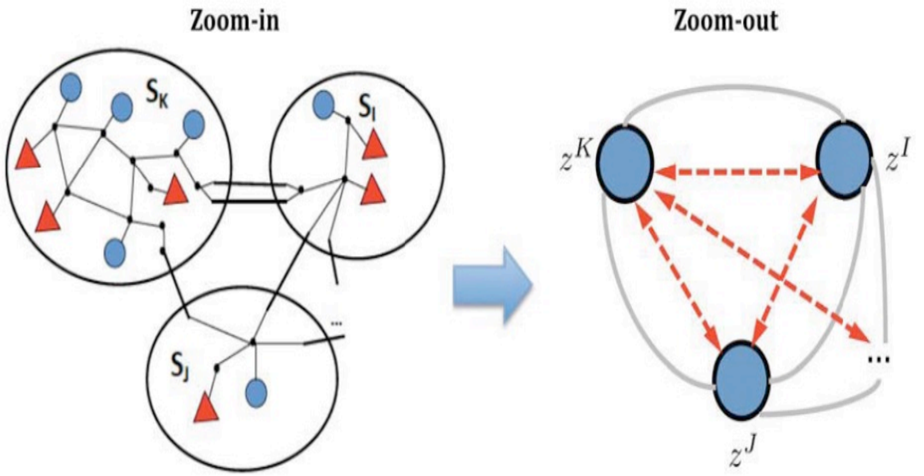
Key notion of interaction variable dynamics and its control

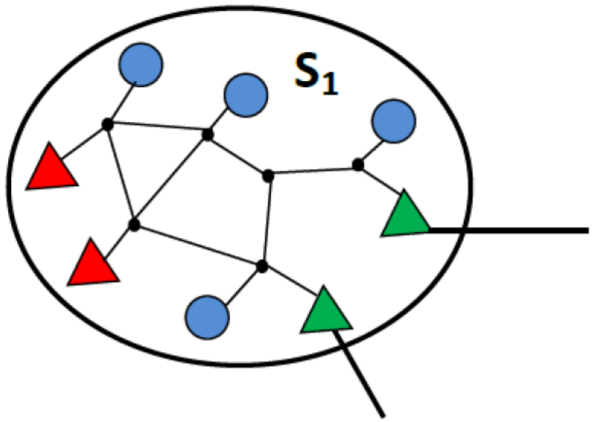
- Interactions variables of area-1 and area-2
- Controlled IntV v.s. uncontrolled IntV

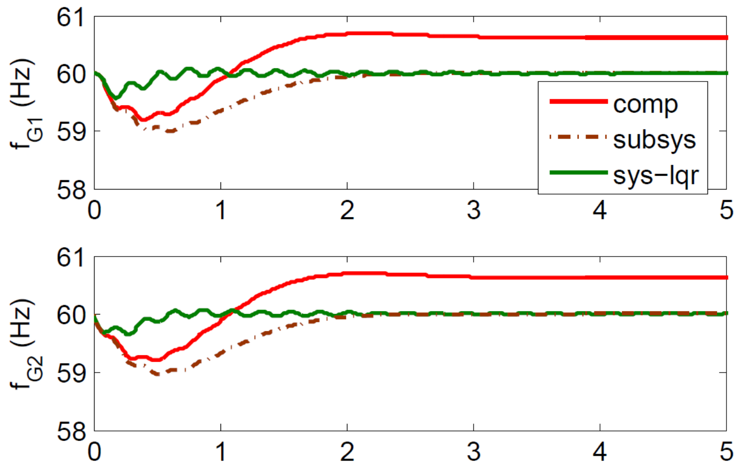




Frequency stabilization using intVar



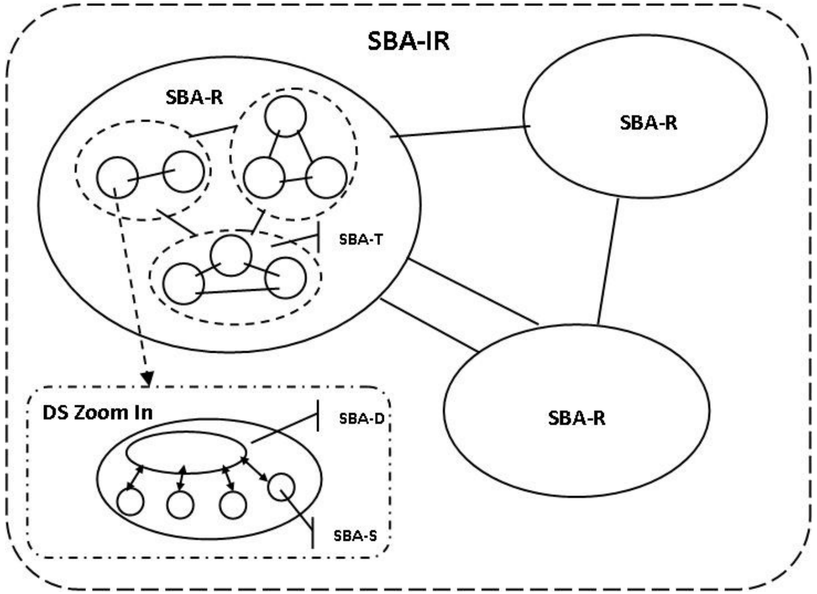


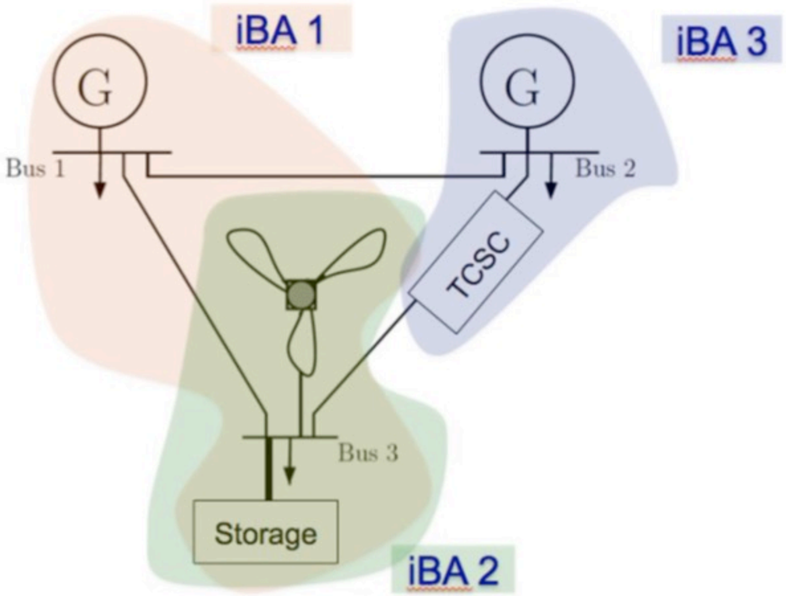


- Dependence of frequency response on power balancing control (generator , BA level, system levels)
- Use of intVars makes these scalable

Is there a more general simple paradigm?
General structure of electric energy systems

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





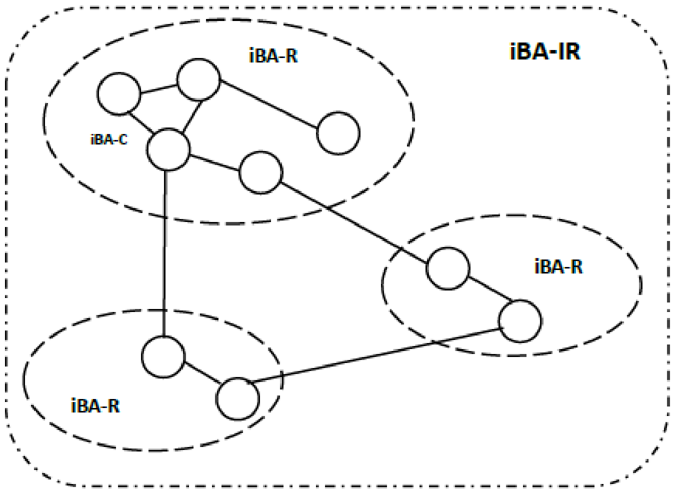
Note: SBAs renamed to iBAs (suggestion by a PSERC member some time ago)

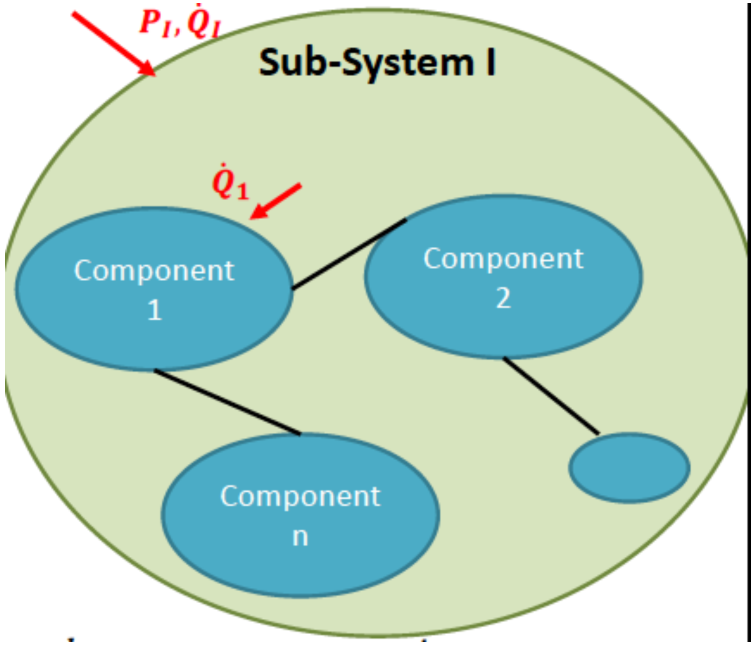
Ilic, M., "Dynamic Monitoring and Decision Systems for Enabling Sustainable Energy Services", Network Engineering for Meeting the Energy and Environmental Dream, Scanning the Issue, Proc. of the IEEE,2011.

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.

Toward a general structure-based simple paradigm?

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





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

Unifying energy-based modeling of dynamics

- Component level (module, S within the SoS)
- Interactive model of interconnected systems
- Model-based system engineering (MBSE)—

--multi-layered complexity

--component (modules) – designed by experts for common specifications (energy; power; rate of change of power)

--interactions subject to conservation of instantaneous power and reactive power dynamics; optimization at system level in terms of these variables

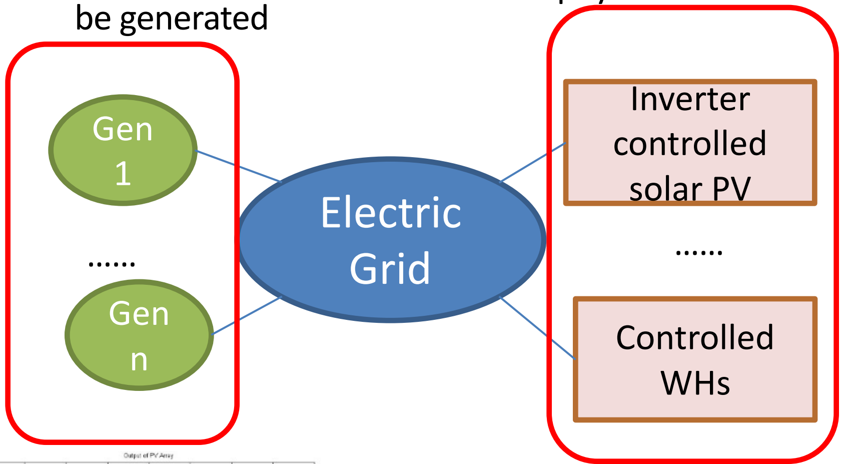
--physically intuitive models

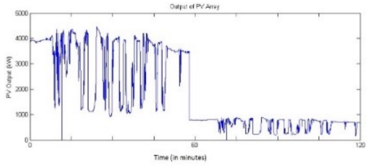
Ilić, Marija D., and Rupamathi Jaddivada. "Multi-layered interactive energy space modeling for near-optimal electrification of terrestrial, shipboard and aircraft systems." *Annual Reviews in Control* (2018).

Unifying energy-based dynamical modeling

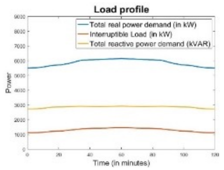
Inertia used as a proxy to rates at which energy can be generated

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) –bas approximated system analysis valid

Basis for energy as a state variable

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

Basis for real power as an interface variable

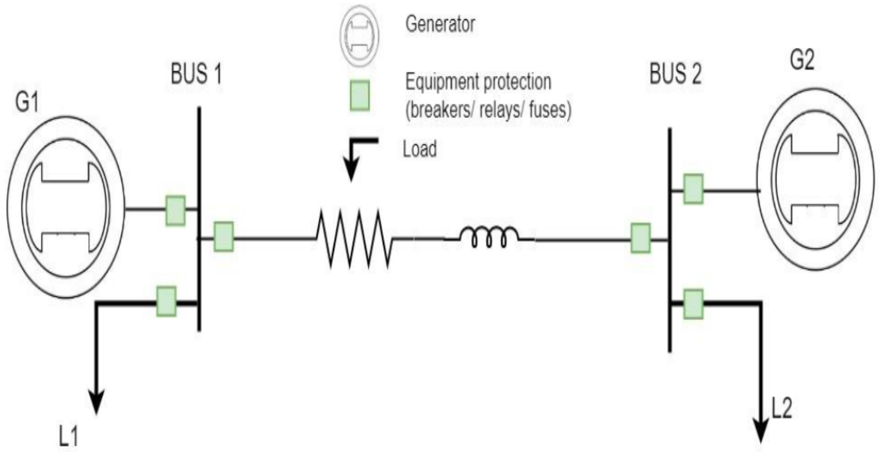
Not all power produced can be delivered fundamentally due to mismatch in rates at which energy conversion processes of connected components tak thermal losses ought to be cap

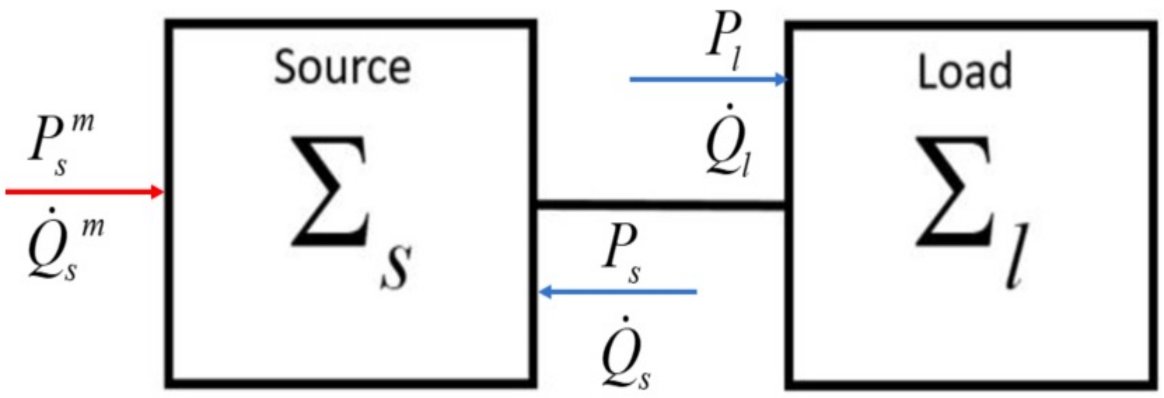
Basis for reactive power as an interface variable

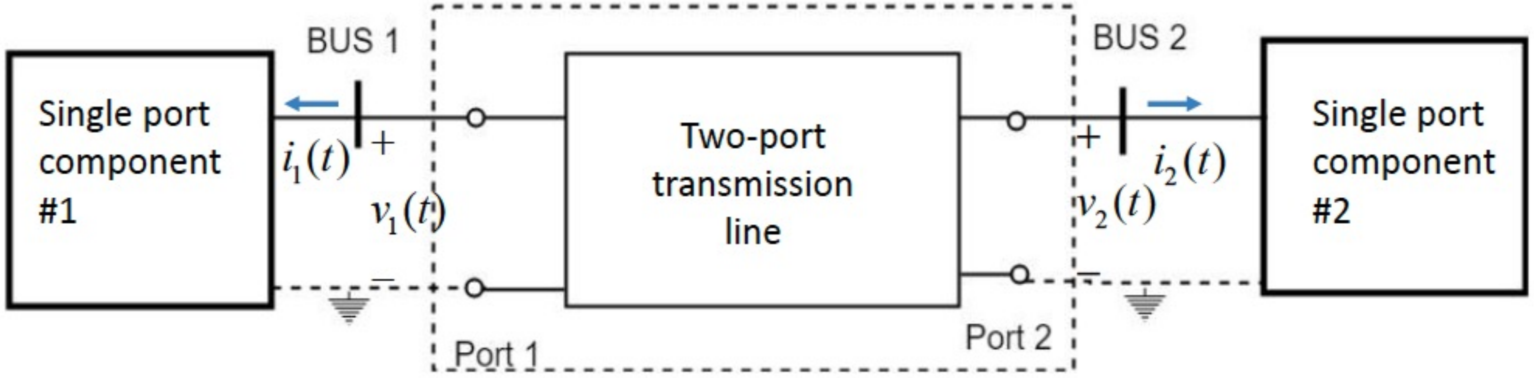
Ilić, M. D., & Jaddivada, R. (2018). Multi-layered interactive energy space modeling for near-optimal electrification of terrestrial, shipboard and aircraft systems. Annual Reviews in Control, 45, 52-75.

EESG @MIT

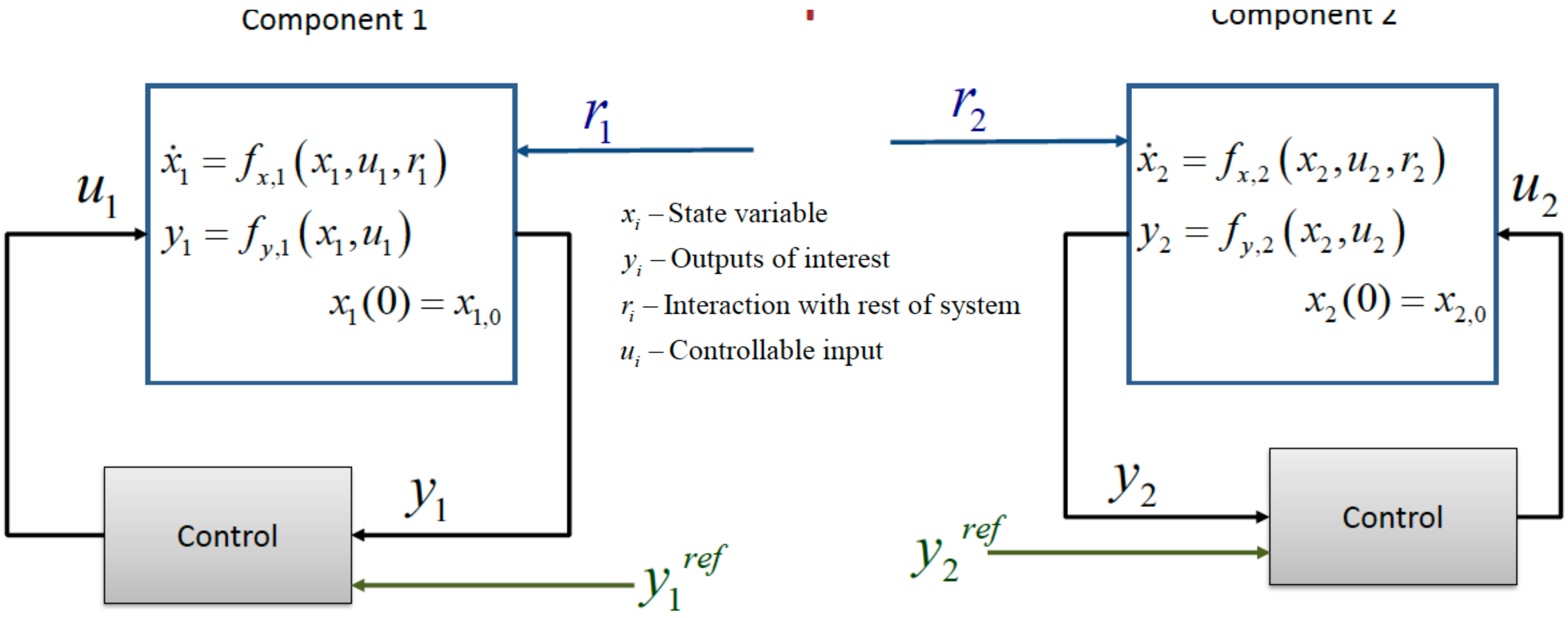
Modular structure --conventional state space







Standalone component modeling in statespace form



Overall energy space model:

$$\dot{E} = -\frac{E}{\tau} + P = p$$

$$\dot{p} = 4E_t - \underbrace{\left(\dot{Q}_L - \dot{Q}_c\right)}_{\text{Net reactive power absorbed}}$$

$$\Rightarrow$$

$$\dot{E} = -\frac{E}{\tau} + P = p$$

$$\dot{p} = 4E_t - \underbrace{\dot{Q}}_{\substack{\text{Reactive power}\\ \text{entering the port}}} + 2\underbrace{\dot{Q}_c}_{\substack{\text{Local reactive}\\ \text{power production}}}$$

New definition of rate of change of reactive power—beyond Time Varying Phasor (TVP) Modeling

Wyatt, J. L., & Ilic, M. (1990, May). Time-domain reactive power concepts for nonlinear, nonsinusoidal or nonperiodic networks. In IEEE international symposium on circuits and systems (pp. 387-390). IEEE.

This is a result of application of generalized Tellegen's theorem since the reactive power entering the port can be split into inductive and capacitive components (assuming linear restive components)

$$\dot{Q} = \dot{Q}_L + \dot{Q}_C$$

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

Energy space modeling of component

Component 1

$$x_{z,1} = \begin{bmatrix} E_1 & p_1 \end{bmatrix}^T$$

$$z_1 = \begin{bmatrix} P_1 & Q_1 \end{bmatrix}^T$$

$$z_2 = \begin{bmatrix} P_2 & Q_2 \end{bmatrix}^T$$

Component 2

$$x_{z,2} = \begin{bmatrix} E_2 & p_2 \end{bmatrix}^T$$

Component 1 dynamics

$$\dot{x}_{z,1} = f_{z,1}\left(E_{t,1}(\dot{x}_1), x_{z,1}, \dot{z}_1\right)$$

where $\quad x_{z,1}(0) = x^0{}_{z,1}$

$$E_i = \frac{1}{2} x_i^T H_i x_i$$

$$p_i = x_i^T H_i \dot{x}_i = x_i^T H_i \left(f_{x,i}\left(x_i, u_i, r_i\right)\right)$$

$$E_{t,i} = \frac{1}{2} \dot{x}_i^T H_i \dot{x}_i$$

Component 2 dynamics:

$$\dot{x}_{z,2} = f_{z,2}\left(E_{t,2}(\dot{x}_2), x_{z,2}, \dot{z}_2\right)$$

$$x_{z,2}(0) = x^0{}_{z,2}$$

$$P_i = \langle r_i, s_i \rangle$$

$$\dot{Q}_i = \left\langle r_i, \frac{ds_i}{dt} \right\rangle - \left\langle \frac{dr_i}{dt}, s_i \right\rangle$$

INTERACTIVE!

EESG @MIT

Stand-alone interactive model in energy space

Closed-loop dynamics in energy space:

$$\dot{x}_{z,i} = A_{z,i}x_{z,i} + B_v E_{t,i} + B_{z,i}\dot{z}_i^{\,r,out}$$

$$x_{z,i}(0) = x_{z,i0}$$

$$\dot{z}_i^{\,r,out} = \begin{bmatrix} P_i^{r,out} \\ \dot{Q}_i^{\,r,out} \end{bmatrix}$$

$$\dot{z}_i^{\,r,out} = \phi_z^{\,r}\left(x_i, \dot{x}_i, \dot{r}_i\right)$$

$$E_{t,i} = \frac{1}{2}\dot{x}_i^T H_i(x_i)\dot{x}_i$$

$$\dot{z}_i^{\,r,in}$$

Closed-loop physical dynamics :

$$\dot{x}_i = A_i^{cl}(x_i)x_i + B_i^r r_i \qquad x_i(0) = x_{i,0}$$

$$\dot{r}_i = \frac{1}{2w_i^r}\left(\dot{P}_i^{r,in} - \dot{Q}_i^{\,in}\right) \qquad r_i(0) = r_{i,0}$$

Why P and Q have been chosen as interface variables?

- P over a time quantifies useful work done
- Q at any time quantifies the associated inefficiencies in power transfer
- Both of them obey conservation laws at the interfaces

Unifying properties of interaction variables

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

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

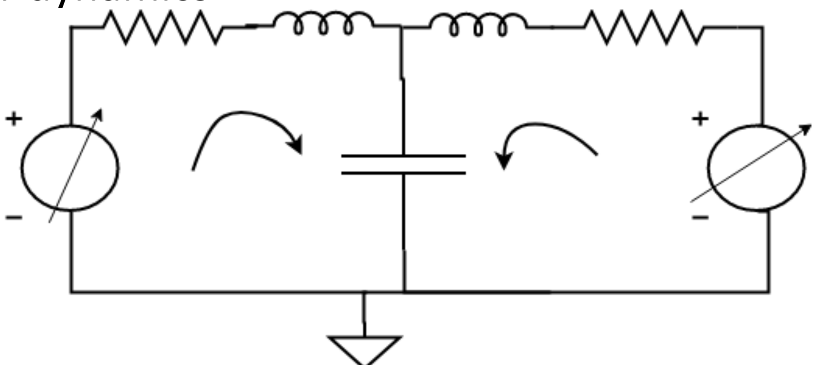
No linearization!
No decoupling!
The same definition

Property 3: (State of art in power systems)
Dynamics of reactive power can be neglected when voltage is not changing

Generalized reactive power:

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

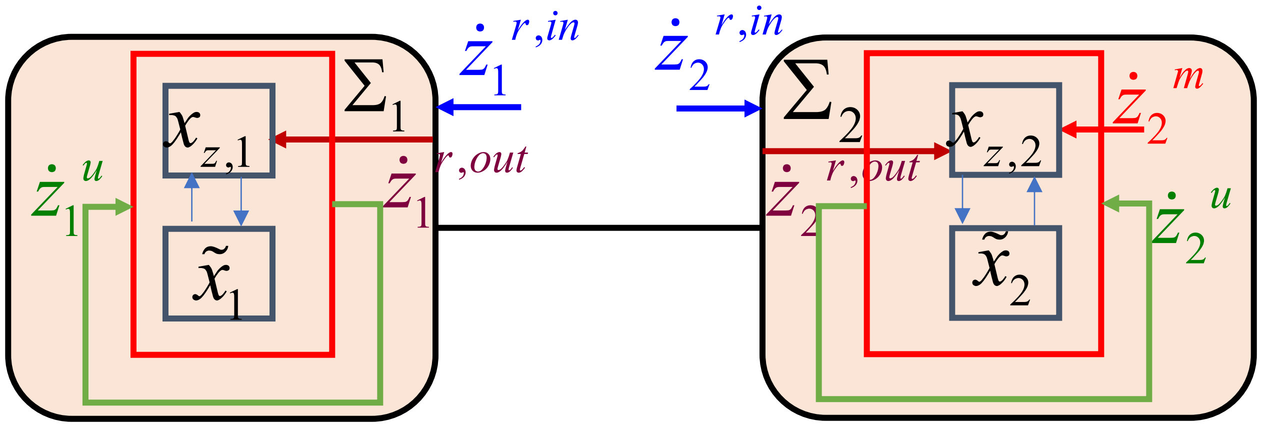
Property 4: (Circulating currents)
Circulating currents are indicative of non-zero reactive power dynamics



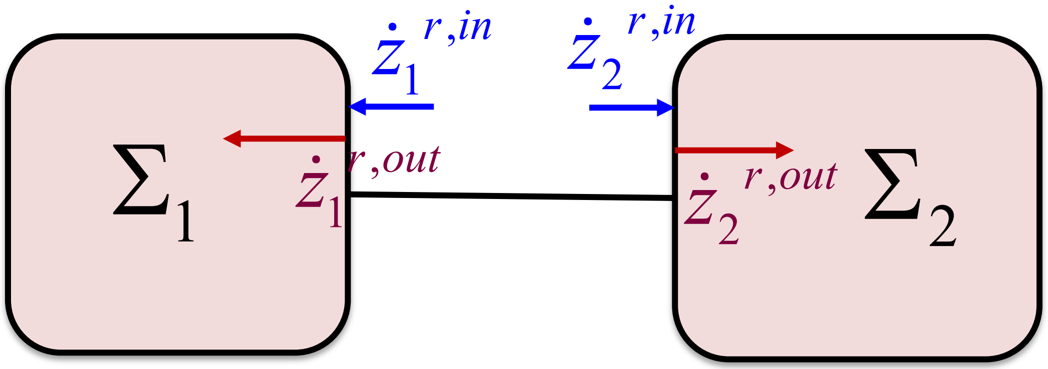
EESG @MIT

Representation of interactions within and across components

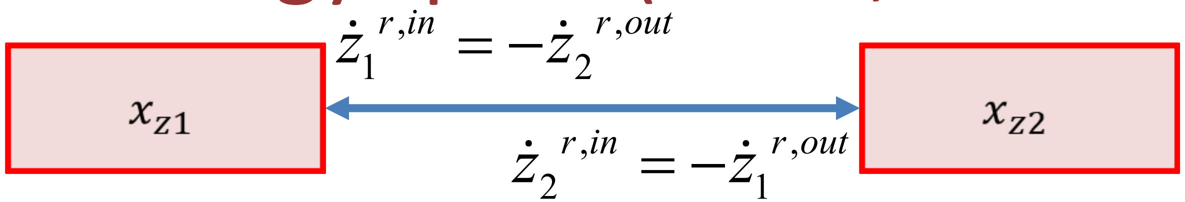
Zoomed-in representation:



Zoomed-out representation:



Structure of interconnected system model in transformed energy space (linear, interactive)



Distributed modular model

$$\dot{x}_{z,1} = A_{z,1}x_{z,1} + B_t E_{t,1} + B_z \dot{z}_1^{r,out}$$

$$\dot{x}_{z,2} = A_{z,2}x_{z,2} + B_t E_{t,2} + B_z \dot{z}_2^{r,out}$$

$$\begin{bmatrix} \dot{z}_1^{r,out} \\ \dot{z}_2^{r,out} \end{bmatrix} = \underbrace{\begin{bmatrix} 0 & -I_{2\times 2} \\ -I_{2\times 2} & 0 \end{bmatrix}}_{L_z}^{-1} \begin{bmatrix} \dot{z}_1^{r,in} \\ \dot{z}_2^{r,in} \end{bmatrix}$$

$$x_{z,i} = \begin{bmatrix} E_i \\ p_i \end{bmatrix} \qquad \dot{z}_i^{r,out} = \begin{bmatrix} P_i^{r,out} \\ \dot{Q}_i^{r,out} \end{bmatrix} \qquad \forall i \in \{1,2\}$$

$$A_{z,i} = \begin{bmatrix} -\frac{1}{\tau_i} & 0 \\ 0 & 0 \end{bmatrix} \qquad B_t = \begin{bmatrix} 0 \\ 4 \end{bmatrix} \qquad B_z = \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}$$

ODE model at interconnection level

$$\dot{\mathbf{x}}_\mathbf{z} = \underbrace{\begin{bmatrix} A_{z,1} & 0 \\ 0 & A_{z,2} \end{bmatrix}}_{\mathbf{A_z}} \mathbf{x_z} + \underbrace{\begin{bmatrix} B_t^{\,T} & B_t^{\,T} \end{bmatrix}}_{\mathbf{B_t}} \mathbf{E_t} + \begin{bmatrix} 0_{2\times 2} & -I_{2\times 2} \\ I_{2\times 2} & 0_{2\times 2} \end{bmatrix} \mathbf{z^{r,in}}$$

$$\mathbf{x_z} = \begin{bmatrix} x_{z,1} \\ x_{z,2} \end{bmatrix} \qquad \mathbf{E_t} = \begin{bmatrix} E_{t,1} \\ E_{t,2} \end{bmatrix} \qquad \dot{\mathbf{z}}^{\mathbf{r,in}} = \begin{bmatrix} \dot{z}_1^{\,r,in} \\ \dot{z}_2^{\,r,in} \end{bmatrix}$$

Interactive energy space model of connected system

$$z_1 = [P_1 \quad Q_1]^T \qquad z_2 = [P_2 \quad Q_2]^T$$

$$x_{z,1} = [E_1 \quad p_1]^T \qquad x_{z,2} = [E_2 \quad p_2]^T$$

Component 1 dynamics

$$\dot{x}_{z,1} = f_{z,1}\left(E_{t,1}(\dot{x}_1), x_{z,1}, \dot{z}_1\right)$$

$$x_{z,1}(0) = x^0{}_{z,1}$$

Component 2 dynamics:

$$\dot{x}_{z,2} = f_{z,2}\left(E_{t,2}(\dot{x}_2), x_{z,2}, \dot{z}_2\right)$$

$$x_{z,2}(0) = x^0{}_{z,2}$$

Interconnection:

$$\dot{z}_1 + \dot{z}_2 = 0$$

$Q_1 + Q_2 \neq 0$ because of initial stored energy

KEY REASON FOR NEEDING/COMPUTING DERIVATIVES!

Modeling of energy dynamics—zoomed in view

Interactive model of component **i**

Interaction model:

$$\dot{x}_{z,i} = A_{z,i}x_{z,i} + B_t E_{t,i} + B_z\left(\dot{z}_i^{u} + \dot{z}_i^{m} + \dot{z}_i^{r,out}\right)$$

$$y_{z,i} = C_{z,i}x_{z,i} + D_z\left(\dot{z}_i^{u} + \dot{z}_i^{m}\right) \qquad x_{z,i}(0) = x_{z,i0}$$

$$\dot{z}_i^{r,in} = -\dot{z}_j^{r,out}$$

$$\dot{z}_i^{r,out}$$

$$\dot{z}_i^{r,out} = \phi_{z,i}(x_i, r_i, u_i, m_i, \dot{z}_i^{r,in})$$

$$E_{t,i} = \frac{1}{2}\dot{x}_i^T H_i(x_i)\dot{x}_i$$

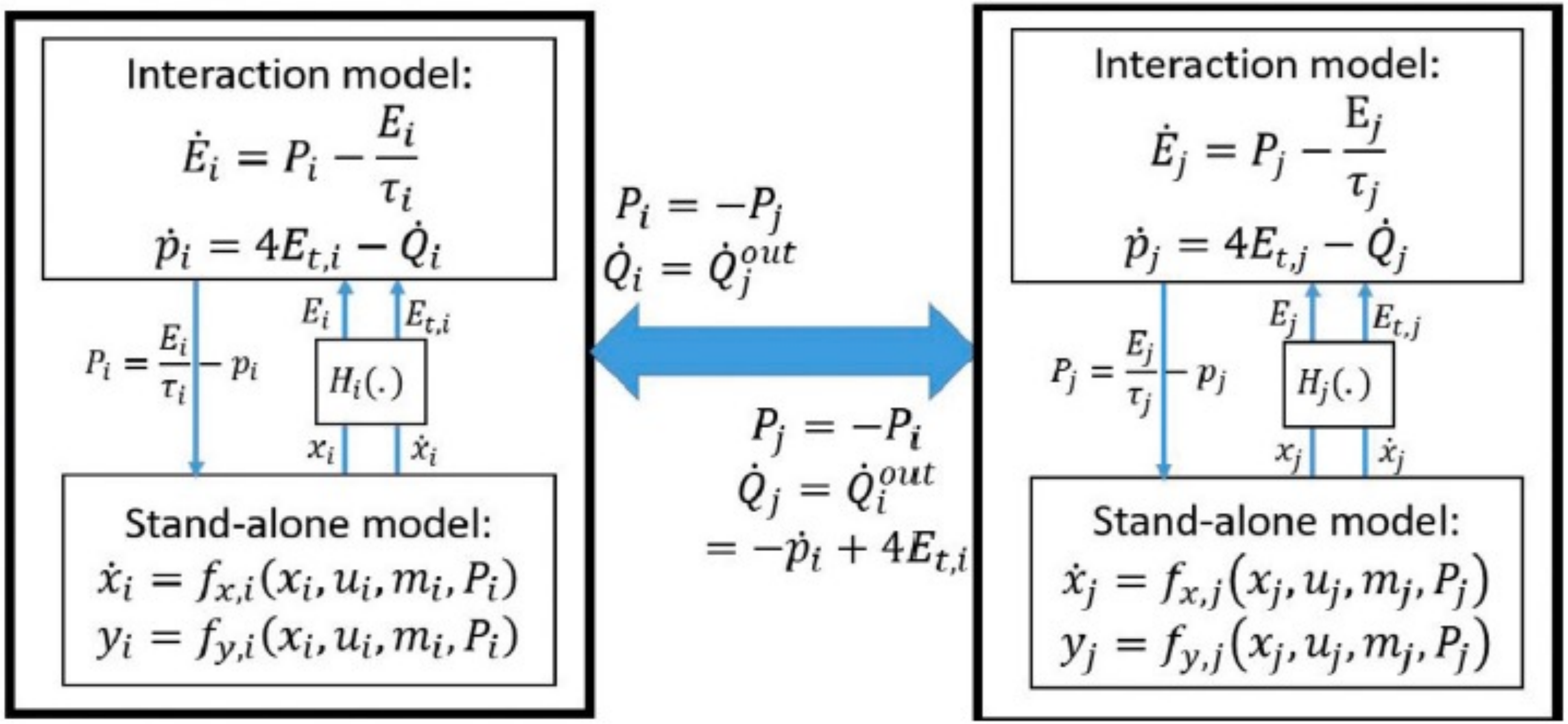
$$\dot{z}_i^{r,in}$$

Open-loop physical dynamics: $\tilde{x}_i(0) = \begin{bmatrix} x_{i0} & r_{i0} \end{bmatrix}^T$

$$\underbrace{\begin{bmatrix} \dot{x}_i \\ \dot{r}_i \end{bmatrix}}_{\dot{\tilde{x}}_i} = \underbrace{\begin{bmatrix} f_{x,i}(x_i) + g_i^{r}(x_i)r_i \\ f_{r,i}(x_i) + g_{r,i}^{r}(x_i)r_i \end{bmatrix}}_{\tilde{f}_{\tilde{x}_i}} + \underbrace{\begin{bmatrix} g_i^{m}(x_i) \\ g_{r,i}^{m}(\tilde{x}_i) \end{bmatrix}}_{\tilde{g}_{\tilde{x}_i}^{m}} m_i + \underbrace{\begin{bmatrix} 0 \\ g_{r,i}^{r}(\tilde{x}_i) \end{bmatrix}}_{\tilde{g}_{\tilde{x}_i}^{z}} \dot{z}_i^{r,in} + \underbrace{\begin{bmatrix} g_i^{u}(x_i) \\ g_{r,i}^{u}(\tilde{x}_i) \end{bmatrix}}_{\tilde{g}_{\tilde{x}_i}^{u}} u_i$$

STAND ALONE COMPONENT

Unified state space modeling: Zoom out aggregate view



iNTER-CONNECTED COMPONENTS

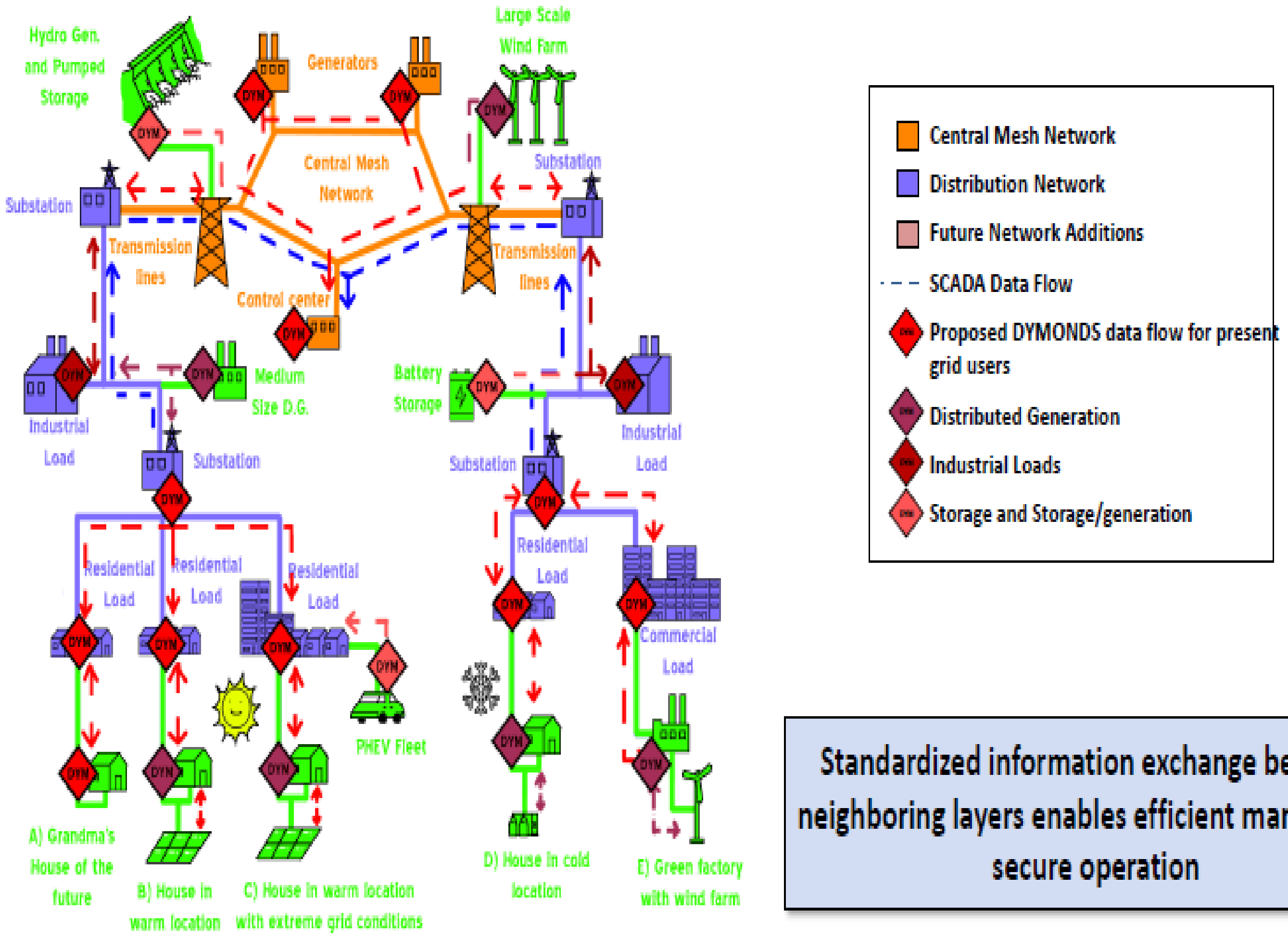
Dynamic Monitoring and Decision-making System (DYMONDS)

- Conventional system operation
  - Centralized decision making
    - ISO knows and decides all
  - Not proper for future electric energy systems
    - Too many heterogeneous decision making components
      : DGs, DRs, electric vehicles, LSEs, etc.

- Dynamic Monitoring Decision-making System (DYMONDS)
  - Distributed decision making system
    - Distributed optimization of multiple components → computationally feasible
  - Individual decisions submitted to ISO (as supply/demand bids)
    - Individual inter-temporal constraints **internalized**
    - Market clearance and overall system balanced by ISO

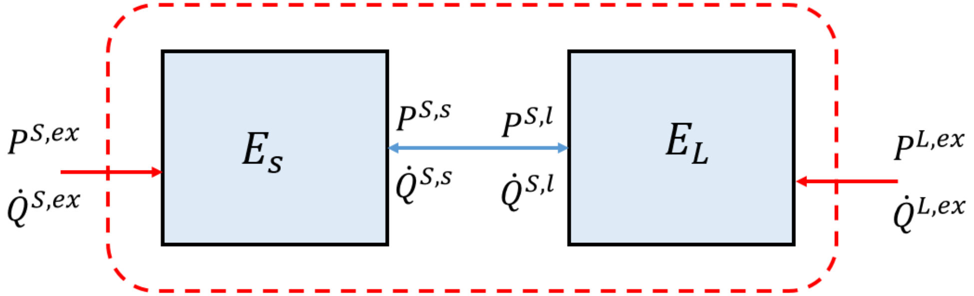
Protocol principles for evolving Dynamic Monitoring and Decision Systems (DyMonDS) architecture

- **Information exchange in terms of energy, power and rate of change of reactive power.** **intVars with physical interpretation as a generalized ACE.**
- BAs transform to iBAs In order to support interactive control and co-design today' s BAs are further organized as iBAs – groups of stakeholders, both utility and third parties, with their own sub-objectives. Each iBA is responsible for electricity services to its members and must communicate its commitments in terms of intVars to participate in electricity services with others
- Next generation SCADA to support information exchange among iBAs As the operating conditions vary, stakeholders process the shared information, and optimize their own sub-objectives, subject to own constraints and preferences; and communicate back their willingness to participate in system-wide integration



Standardized information exchange between neighboring layers enables efficient markets and secure operation

Optimization problem formulation in energy space



$$\min_{\substack{P^{S,s}(t),P^{S,l}(t),\dot{Q}^{S,s}(t),\\ \dot{Q}^{S,l}(t),E_t^{S,s}(t),E_t^{S,l}(t)}} \int_0^t \dot{Q}^{S,s}(\tau)^2 + \dot{Q}^{S,l}(\tau)^2 d\tau$$

Constraint Set 2:
Source Interaction dynamics:

$$\dot{E}_s(t) = p_s(t) =$$
$$= P^{s,s}(t) + P^{s,ex}(t) - \frac{E_s(t)}{\tau_s}$$
$$\dot{p}_s(t) = 4E_{t,s}(t) - \dot{Q}^{s,g}(t) - \dot{Q}^{s,ex}(t)$$

$$P^{S,s}(t) = P_s(t); Q^{S,s}(t) = Q_s(t)$$
$$E_{t,s} = E_s(\dot{x}_s)$$

Constraint set 1:
Interconnection constraints:

$$P^{s,g} + P^{L,g} = 0$$
$$\dot{Q}^{s,g} + \dot{Q}^{L,g} = 0$$

Dissipativity constraint

$$\dot{p}^{s,ex} + \dot{p}^{L,ex} \leq \frac{\dot{E}_s}{\tau_s} + \frac{\dot{E}_L}{\tau_L}$$

Real and Reactive Power Limits

$$P^{g,min} \leq P^{S,g} \leq P^{g,max}$$
$$P^{l,min} \leq P^{S,l} \leq P^{l,max}$$
$$\dot{Q}^{g,min} \leq \dot{Q}^{S,g} \leq \dot{Q}^{g,max}$$
$$\dot{Q}^{l,min} \leq \dot{Q}^{S,l} \leq \dot{Q}^{l,max}$$

Constraint Set 3:
Load Interaction dynamics:

$$\dot{E}_l(t) = p_l(t) =$$
$$= P^{s,l}(t) + P^{l,ex}(t) - \frac{E_l(t)}{\tau_l}$$
$$\dot{p}_l(t) = 4E_t^l(t) - \dot{Q}^{s,l}(t) - \dot{Q}^{L,ex}(t)$$

$$P^{S,l}(t) = P_l(t); Q^{S,l}(t) = Q_l(t)$$
$$E_{t,l} = E_l(\dot{x}_l)$$

Constraint set 4:
Source Stand-alone Component dynamics:

$$\dot{x}_s(t) = f_{x,s}(x_s(t), u_s(t), P_s(t))$$
$$y_s(t) = f_{y,s}(x_s(t), u_s(t), P_s(t), \dot{Q}_s(t))$$
$$u_s^{min} \leq u_s(t) \leq u_s^{max}$$
$$y_s^{min} \leq y_s(t) \leq y_s^{max}$$

Constraint set 5:
Load Stand-alone Component dynamics:

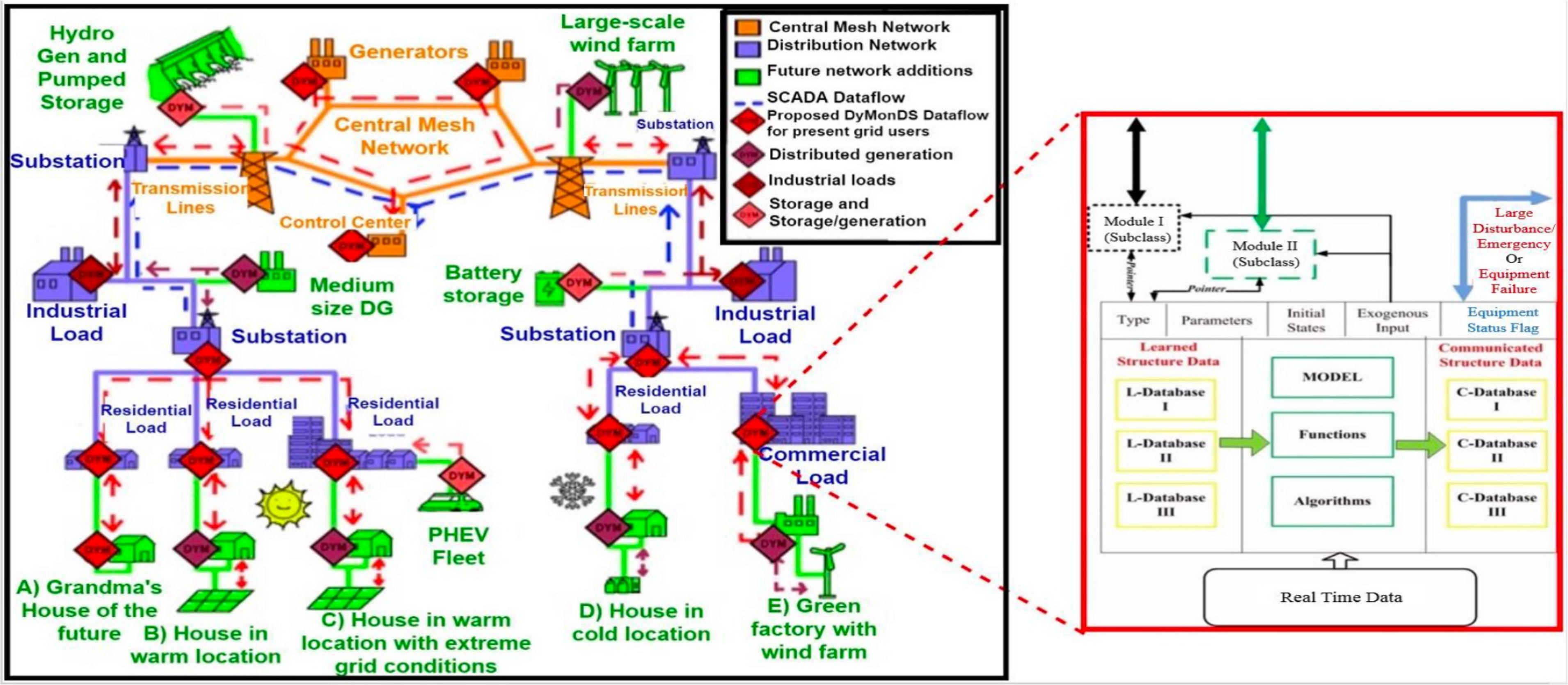
$$\dot{x}_l = f_{x,l}(x_l, u_l, P_l)$$
$$y_l = f_{y,l}(x_l, u_l, P_l, \dot{Q}_l)$$
$$u_l^{min} \leq u_l \leq u_l^{max}$$
$$y_l^{min} \leq y_l \leq y_l^{max}$$

Ilic, M., & Jaddivada, R. (2020). Unified value-based feedback, optimization and risk management in complex electric energy systems. *Optimization and Engineering*, *21*, 427-483.

MAJOR NEED FOR NEXT GENERATION SOFTWARE

- COMPLEXITY EMBEDDED IN THE LOWER LAYERS FOR ENABLING ``BETTER” SPECIFICATIONS (E_T,P,dQ/dT) – automation, smarts, ML, predictions; storage/EV integration
- AGGREGATION OVER TIME AND STAKEHOLDERS MANAGING INTERACTIONS THROUGH MINIMAL COORDINATION
- AMPLE EVIDENCE OF ENHANCED RELIABILITY, EFFICIENCY AND RESILIENCY

Digital twin that might work*



The challenge of multi-layered interactive computing: Accurate and efficient derivatives

*Ilic, M., Jaddivada, R., & Gebremedhin, A. (2023). Unified modeling for emulating electric energy systems: Toward digital twin that might work. In *Research Anthology on BIM and Digital Twins in Smart Cities* (pp. 107-135). IGI Global.

Conclusions—

- Multi-level transformed state space formulation of decision making in the changing electric energy industry lends itself to non-convex dual optimization problems
- Natural alignment of economic incentives, efficient scheduling and end user choice
- Can be used for establishing standards protocols and giving the right incentives
- Next step– distributed management of uncertainty
- Lower layer specifications must be defined in terms of common technology-agnostic variables