FROM HIERARCHICAL CONTROL TO FLEXIBLE INTERACTIVE ELECTRICITY SERVICES: A PATH TO DECARBONIZATION

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Electricity provision today*

- Top down centralized dispatch and control of large-scale power plants to:
- Task 1) supply predictable system demand;
- Task 2) Compensate predictable transmission losses;
- Task 3) Schedule generation so that there are no ``congestion” delivery grid problems;
- Task 4) Have sufficient regulation reserve to regulate frequency and voltage deviations caused by hard-to-predict slow power imbalances;
- Task 5) Have sufficient security reserve to supply predictable demand reliably even during the worst cas (N-1/N-2) outages;
- Task 6) Provide service during extreme events (N-k, k>>2) in a resilient way

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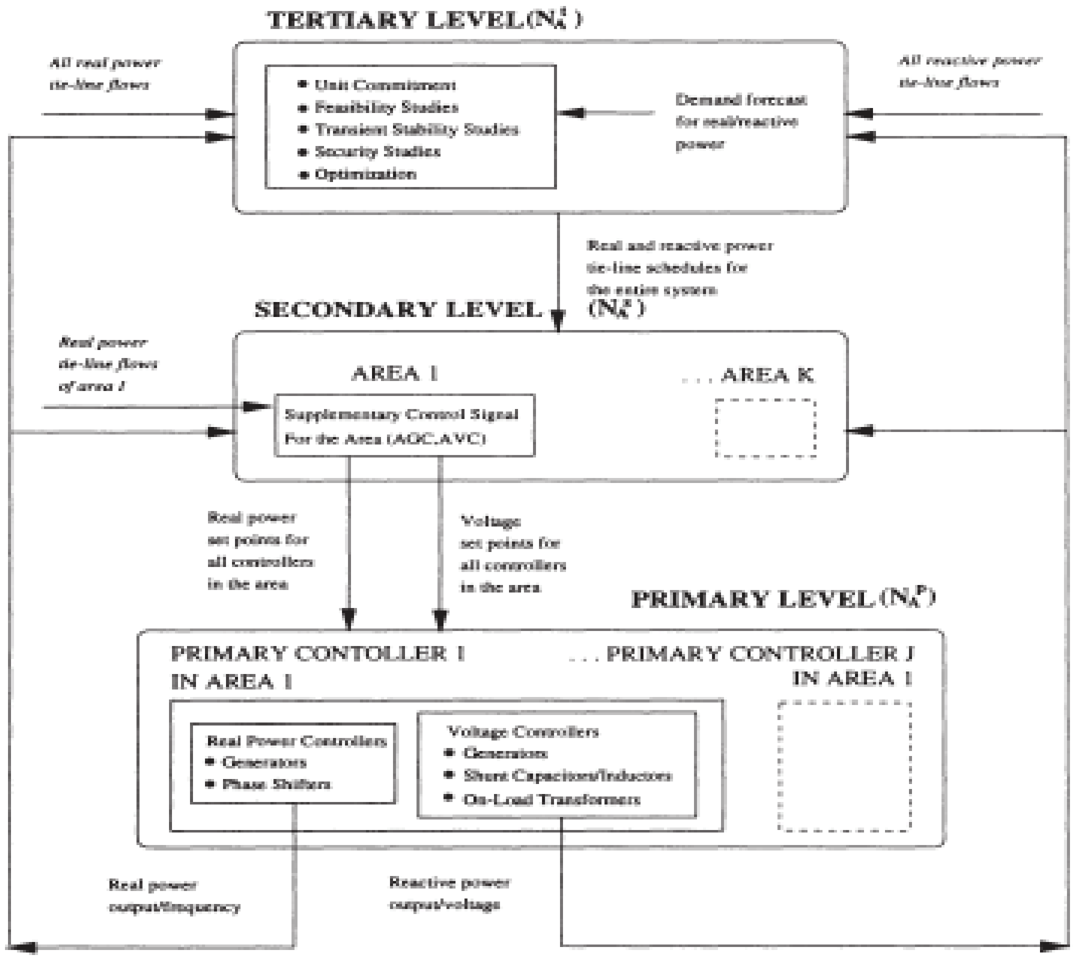
*Ilić, Marija, and Francisco Galiana. "Power systems operation: old vs. new.“*Power Systems Restructuring*. Springer, Boston, MA, 1998. 15-107.

Today’s hierarchical control *



❖Implied assumptions

- P/Q decoupling
- Time scale separation
- Linearized control of generators
- Mainly Bulk Power System (>69kV)

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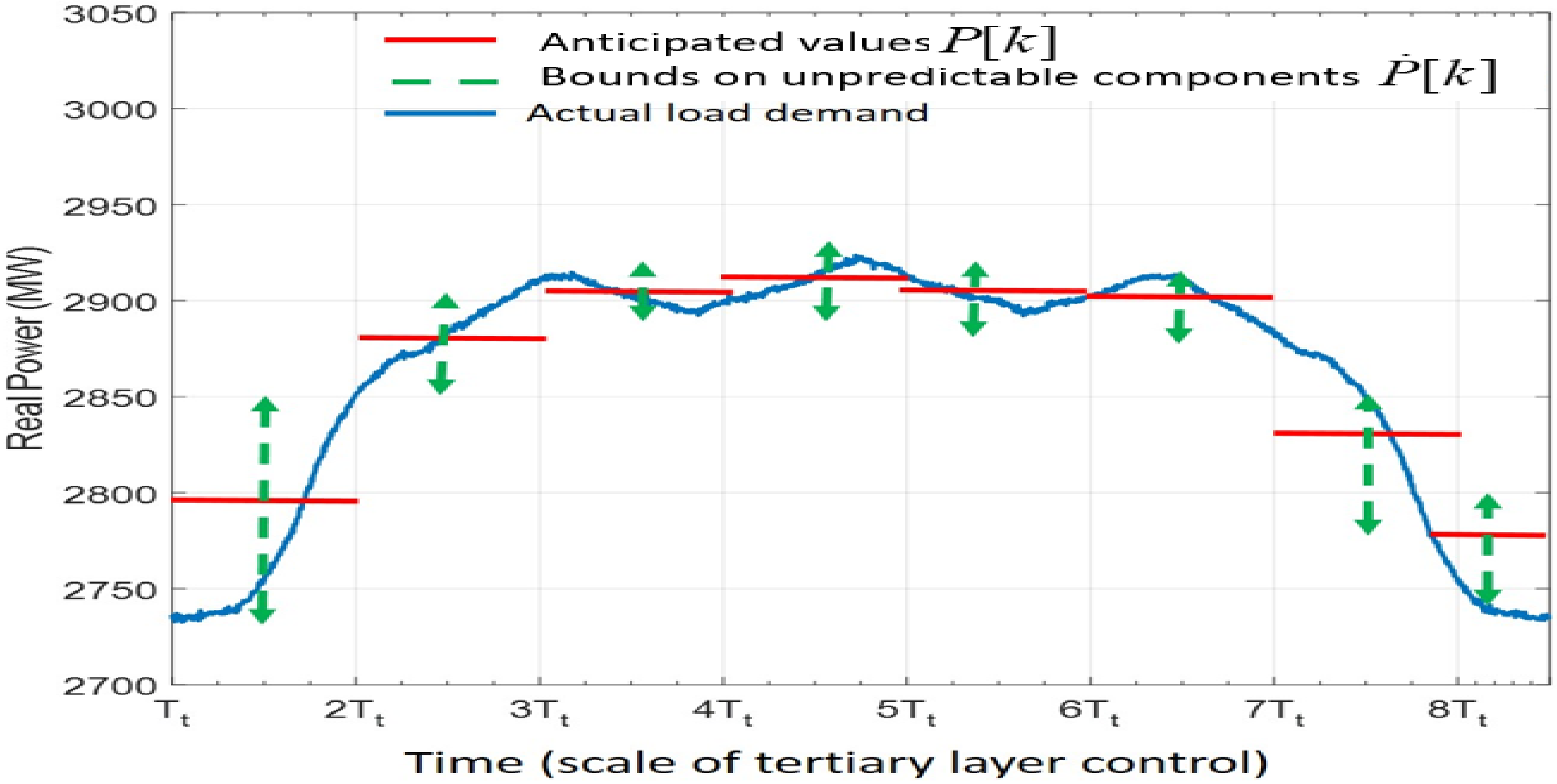
*Ilic, Marija, and Shell Liu. *Hierarchical power systems control: its value in a changing industry*. Springer Science & Business Media, 2012.

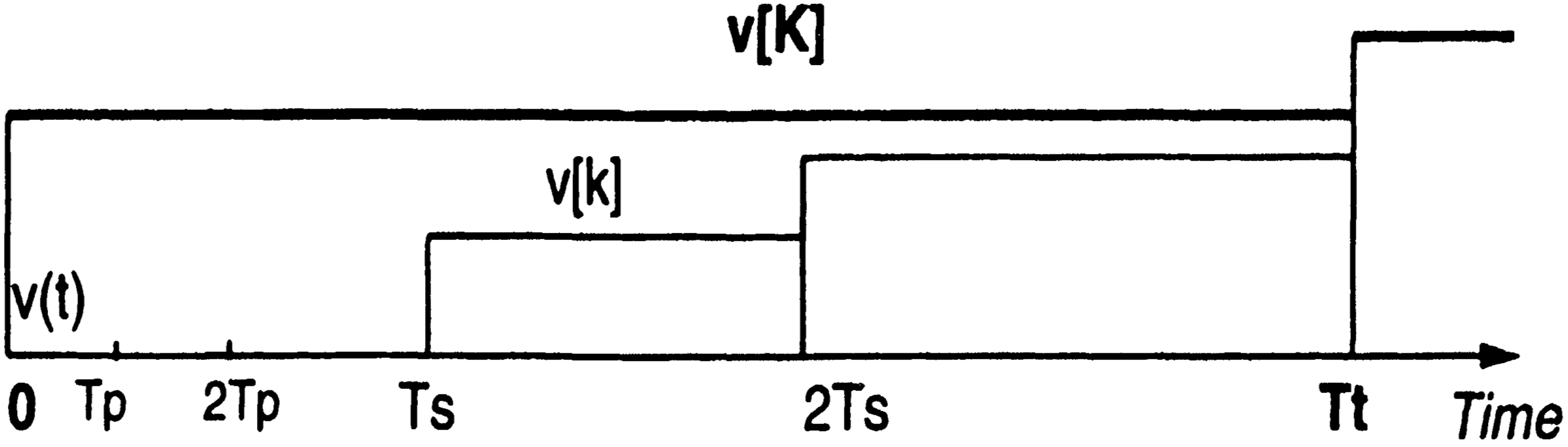
Basis for temporal hierarchies (load induced)



$$P_L = P_L(t) + P_L[k] + P_L[K] \qquad k, K = 0, 1, \cdots$$

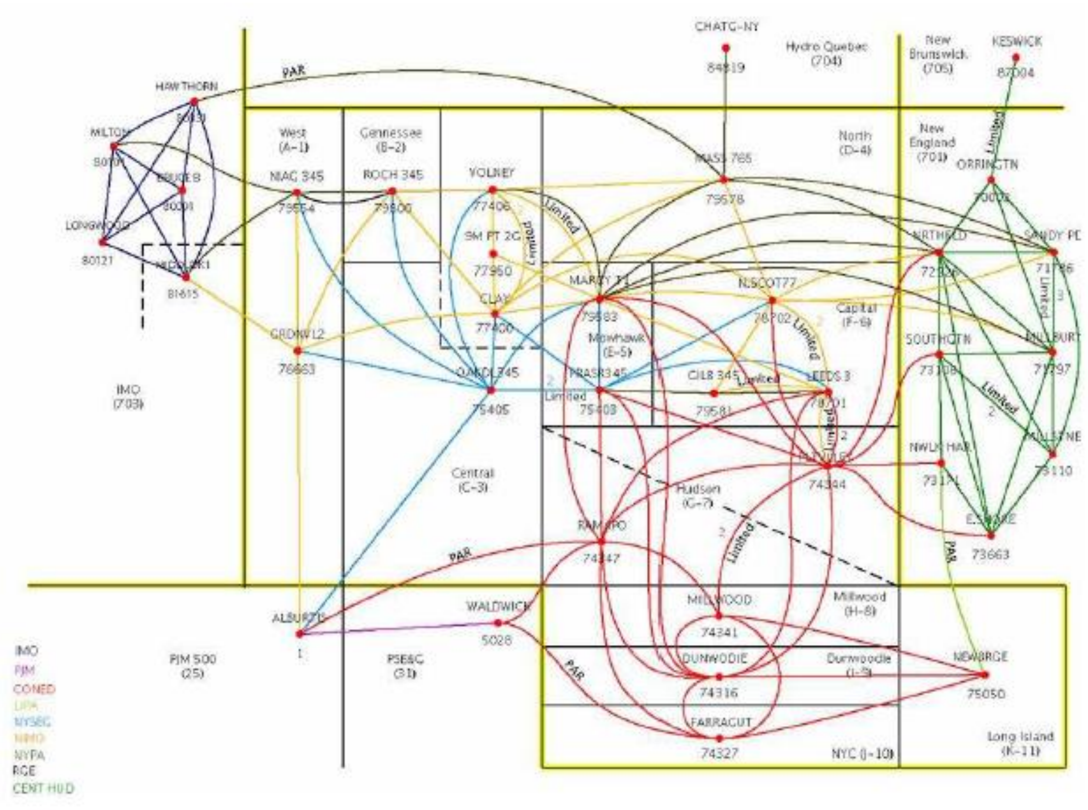
$$Q_L = Q_L(t) + Q_L[k] + Q_L[K] \qquad k, K = 0, 1, \cdots$$

Basis for hierarchical control



- PRIMARY CONTROL --- FASTEST TIME SCALE (T_p), SMALLEST MODULES (equipment)
- SECONDARY CONTROL – SLOWER TIME SCALE (T_s), MEDIUM SIZE MODULES (control areas)
- TERTIARY CONTROL– SLOWEST TIME SCALE (T_t), LARGEST MODULES (system)

Today's wicked problem of energy services



Temporal, spatial and governance complexity of the physical system

Contradicting Interests of entities:

"We want to sell as much as possible to maximize our profit"

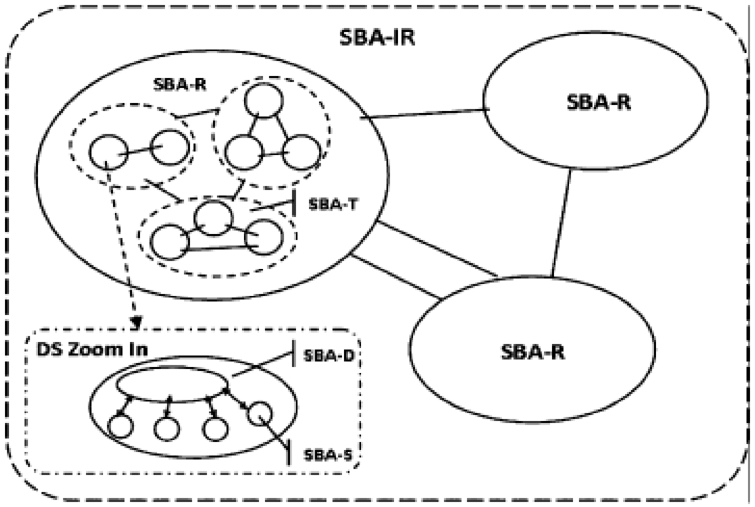
"We want to buy at a low price"

"We have no control on ourselves"

Un-aligned sub-objectives

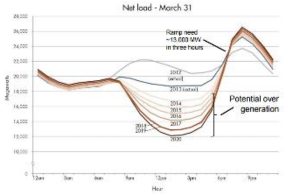
Emerging fundamental needs

- 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**

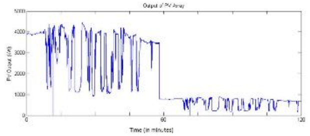


Intelligent Balancing Authorities (iBAs)

Temporal inter-twining

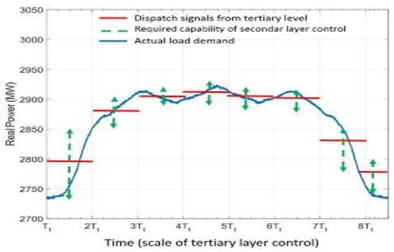


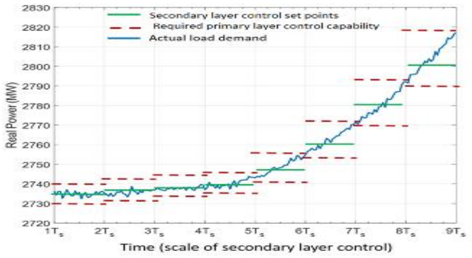
Aggregate effect of solar



Local solar

Hard to predict inputs





Nonzero mean effects

Ilić, M., Carvalho, P. M., & Lessard, D. (2021, July). Minimal Coordination of Dynamic Reserves for Flexible Operations at Value: The Case of Azores Islands. In *2021 IEEE Power & Energy Society General Meeting (PESGM)* (pp. 1-5). IEEE.

New Flexibility Market Models in Europe

- Flexibility market models developed in recent years in EU can be divided into two categories
  - Market platforms in which generators and demand (and aggregators) can offer their flexibility and DSOs and TSOs can procure it.
  - Aggregator platforms where generators and demand can provide flexibility through an independent aggregator or a supplier acting as an aggregator.
- Market structures vary. The majority corresponds to a one-sided market where generators and demand compete to fulfill the service requirements set by DSOs and/or TSOs

Ilic, M., Carvalho, P., **FROM TODAY'S HIERARCHICAL CONTROL TO END-TO-END FLEXIBLE INTERACTIVE ELECTRICITY SERVICES,** FERC Technical Conference on Increasing Market and Planning Efficiency through Improved Software **Docket No. AD10-12-012 (Washington, DC) June 22-24, 2021**

Need to enhance today's hierarchical control: Basic limits

Outmoded control paradigm

- Static, deterministic
- Central EHV/HV/MV grid control;
- Large preventive reserves;
- No real time corrective actions
- No participation of MV/LV/DERs

What needs to be done

- Efficient energy service requires temporal, spatial and functional alignment of energy resources and demand
- T&D system needs to be operated to integrate the growing number of DERs, storage and intermittent resources in a flexible data-enabled way in order to manage uncertainties in an efficient manner

Resulting limitations

- Significant waste through excess reserves (typically 20-30% unused reserves)
- Significant waste due inefficient use of existing infrastructure (only 30% of transmission capacity currently used)
- Long distance transmission very costly, and limits resilience (e.g. California)
- Limits on proportion of renewables that can be accommodated (In Puerto Rico, system claims that 15% is max, our simulations show that much higher transmission capacity utilization is possible with no change in physical transmission system.)
- Lack of resilience to major storms, failures, attacks
- Lack of ability for communities, other stakeholders to "push envelope" on environmental impact, efficiency without major sacrifices in scale/pooling efficiency

Ilic, M., Lessard, D., A distributed coordinated architecture of electrical energy systems for sustainability, in Ilic_LessardEESGatMITWP_dec302020,MIT.

Challenges—It may not work!

- **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

- **Design and demonstration of end-to-end next generation SCADA (DyMonDS); co-design on today's BPS SCADA**

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

System enhancements needed—hidden traps

- ***A (tertiary level controllers*)**: should have adaptive performance metrics and optimize over all controllable equipment *(not the case)*
- ***B (secondary control-droops):*** *modeling often hard to justify (droops only valid under certain conditions)*
- ***C (primary control)*:** A combination of primary and secondary control should guarantee that commands given by microgrid controller are implementable (stable and feasible). *Huge issue—hard to control power/rate of change of power while maintaining voltage within the operating limits!*
- *Note: Control co-design key to improved performance*

Question 1: Resilient and reliable scheduling

From voltage constrained decision making (DCOPF + AC power flow) to coupled AC Optimal Power Flow

- Given an existing system, how to operate new power plants without experiencing power delivery problems.
- Given an existing system, how much new, renewable, generation to build and at which locations.
- Assess the effect of different pricing rules for integrating renewable resources on long- and short-term economic efficiency and the ability to recover capital investment cost.

ACOPF is the key software for co-optimizing power generation and voltage setting

Why is DCOPF insufficient?
With increased renewable penetration, it no longer is possible to dispatch real power with DCOPF well enough without optimizing the voltage settings

Voltage ``congestion” management using AC OPF

- The need to have ***ACOPF-based scheduling*** instead of ***AC power flow-based analyses*** tools
- Adjustments are supposed to work for both “normal” and “abnormal” conditions. (Task 5,Task 6) can also be enhanced significantly by using AC OPF*
- ACOPF-based mitigation for non-time-critical abnormal conditions is very similar to the one with normal conditions
- ***Major assumption:*** sufficient automation is in place to ensure stable system over operating ranges

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*Ilic, M., Ulerio, R. S., Corbett, E., Austin, E., Shatz, M., & Limpaecher, E. (2020). A Framework for Evaluating Electric Power Grid Improvements in Puerto Rico.

From analysis to optimization: Features of AC-XOPF

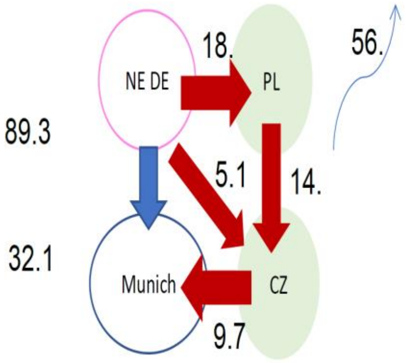
- Having the ability to find a solution within specified network and hardware constraints
- Having the ability to optimize with respect to all available decision variables, such as real power generation, demand, and T&D voltage-controllable equipment
- Providing as part of its output optimization sensitivities
- Providing support of effective resource management according to several optimization objectives
- ***Providing as part of its output LMPs***, which are sensitivities of the performance objective with respect to power injection change at each node in the network

$$\mathrm{LMP}_i = \frac{\delta J}{\delta P_i}$$

AC-XOPF is capable of adaptively switching between using different performance metrics. This is essential for reconciling reliability and efficiency on-line when system conditions and topology change significantly over time

If adopted, it will be successful (demonstrations up to date, normal operations)

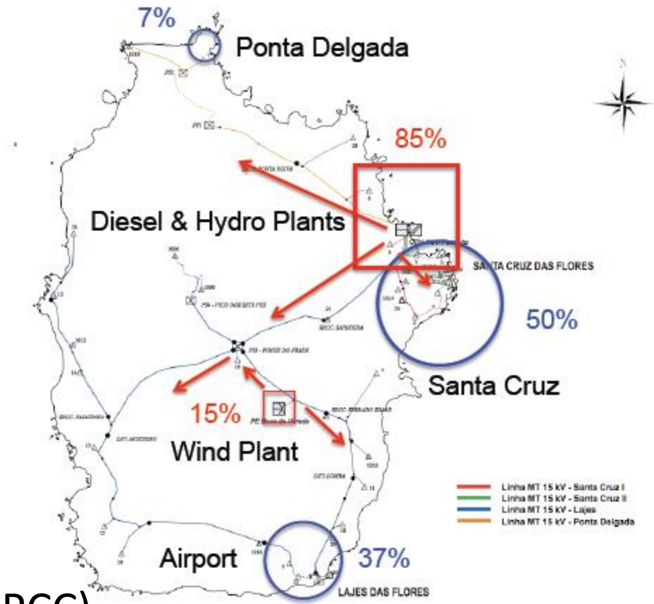
Wind power delivery from NW Germany to Bavaria



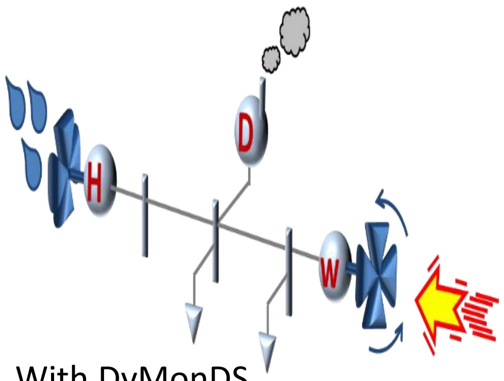
With current grid control
89.3 GW generated
32.1 GW delivered

With DyMonDS
30 GW generated
23 GW delivered

100% green Azores Islands, Portugal

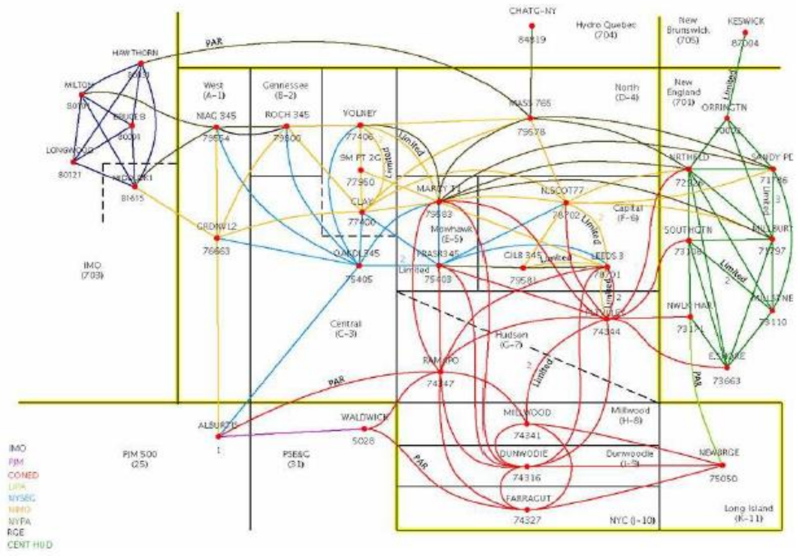


With current control – lots of power from diesel



With DyMonDS
No diesel
Wind and hydro only

Complex electric energy system in the Northeast (NPCC)



Limits on moving power “around” area
Lack of resilience to climate, cyber, operator/equipment
Failure to engage “campuses” and small DERs as iBAs
No integration across systems (electricity, nuclear, gas, hydrogen?)

- Enabling 1GW clean power transfer from Niagara to NYC
- Seamless integration of DERs

Optimization in energy space

- Optimization problems for coordinating iBAs become linear convex optimization problems in the energy space
- Optimizers (aggregators, ISOs, markets) to find the best values from the range specified by the iBAs.
- Win-win protocol
- The protocol is a win-win protocol, since all entities operate within the ranges they selected. If it is not possible to find feasible soluthese primal-dual optimization protocols in energy space can be mapped into corresponding pricing.

Ilic M, Jaddivada R. Unified value-based feedback, optimization and risk management in complex electric energy systems. Optimization and Engineering. 2020 Feb 22:1-57.
Ilic, Marija, Lessard, Don, `` A distributed coordinated control paradigm of the electrical grid for resilience and sustainability", MIT White paper, 2020 (under preparation, available at request)

Question 2:Enabling feasible and stable control?

❖Interactive model of interconnected systems

--multi-layered complexity

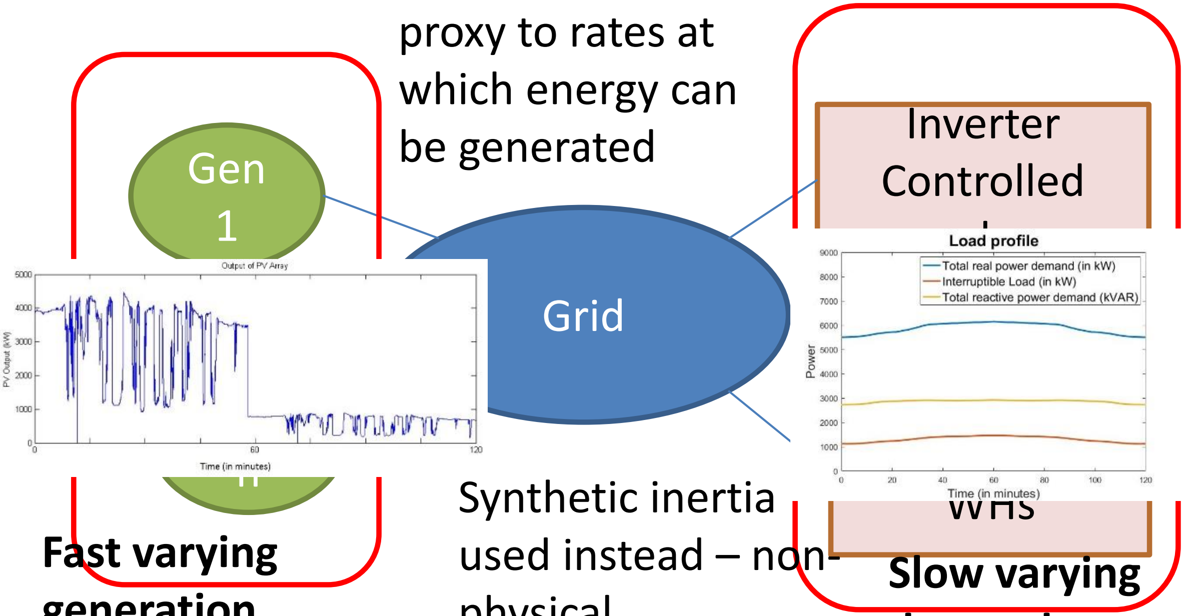
--component (modules) – designed by experts for common specifications (energy; power; rate of change of reactive power)

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

--physically intuitive models

Basis for standardized information -enhancing ACE

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



Fast varying generation

Synthetic inertia used instead – non-physical

Slow varying demand

Not all power produced can be delivered fundamentally due to mismatch in rates at which energy conversion processes of connected components take place – non thermal losses ought to be captured.

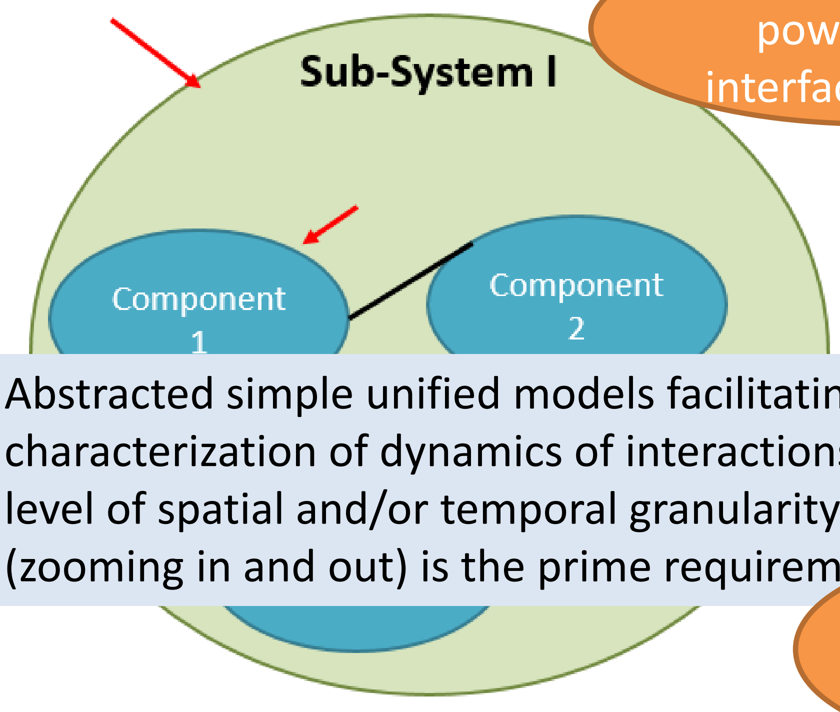
Ultimate objective of power delivery efficiently across the grid is required. Right performance metric for quantification of inefficiency thus is critical

Heterogeneous end-end energy conversion processes modeling is becoming critical - inertia (or synthetic inertia) – based approximated system analysis no longer are valid

Basis for energy as a state variable

Power conservation laws always hold at the interfaces of components and/or sub-systems.

Basis for real power as an interface variable



Abstracted simple unified models facilitating characterization of dynamics of interactions at any level of spatial and/or temporal granularity (zooming in and out) is the prime requirement

Basis for cooperative control

Proposed principles for operating protocols

- First principle– generalize today’s AGC standards on Balancing Authorities (BAs) in terms of area control error (ACE) into standards/protocols for intelligent Balancing Authorities (iBAs). New common variables characterizing input-output interactions between iBAs. These extensions set protocols for storage; inverter controlled PVs; demand DERs; conventional generators; and T&D components.
- Second principle—an ``optimal” social ecological energy system (SEES) should evolve through the feedforward/feedback interactions
- Third principle –design/control of components and their interactions for optimizing efficiency (maximize real work)

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).

Overall energy space model:

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

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

$$\Rightarrow$$

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

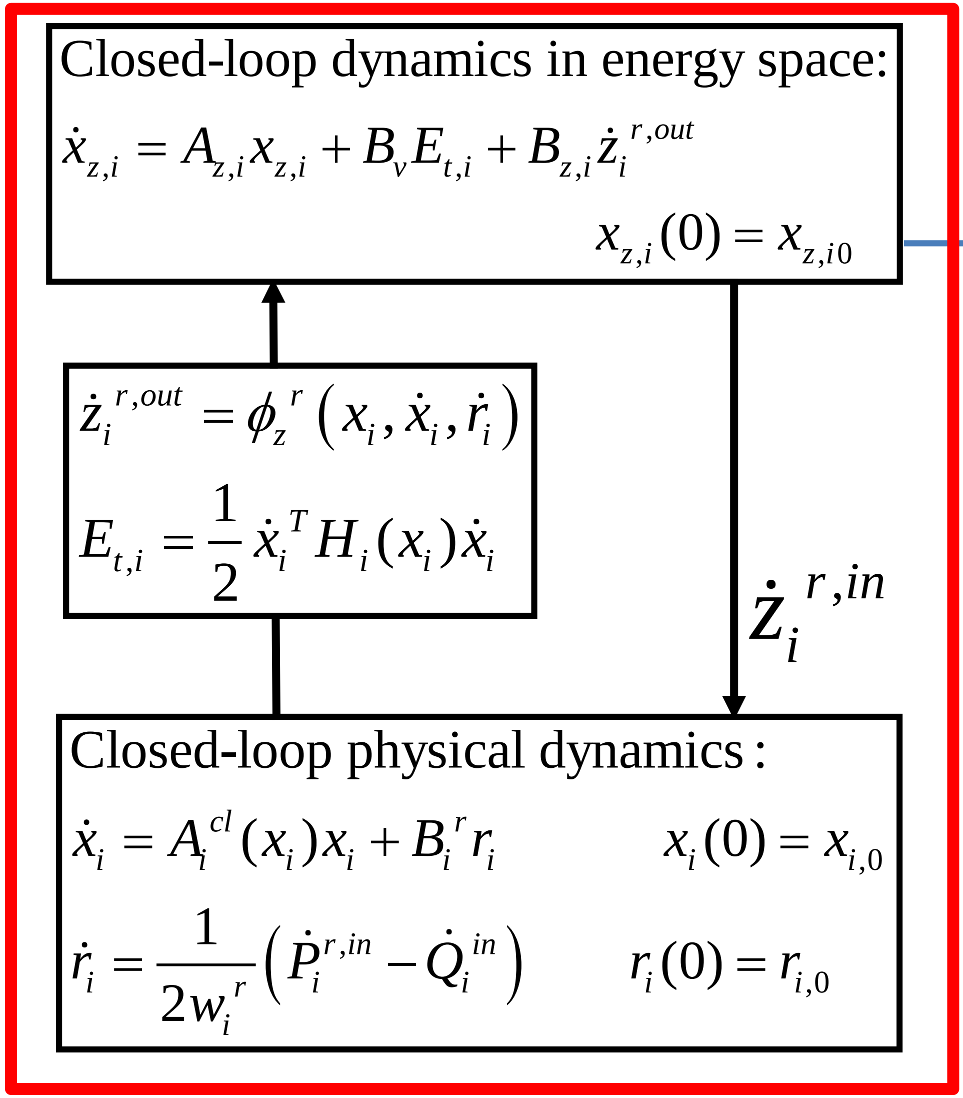
$$\dot{p} = 4E_t - \underset{\substack{\text{Reactive power}\\ \text{entering the port}}}{\dot{Q}} + 2\underset{\substack{\text{Local reactive}\\ \text{power production}}}{\dot{Q}_c}$$

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.

Stand-alone interactive model in energy space



Closed-loop dynamics in energy space:

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

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

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

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

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

Closed-loop physical dynamics :

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

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

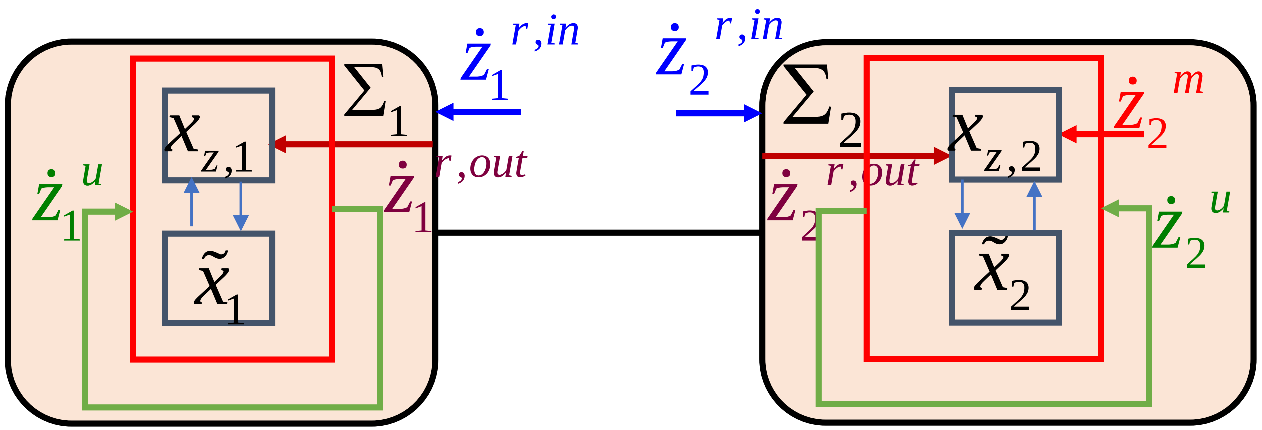
$$\dot{z}_i^{r,out} = \begin{bmatrix} P_i^{r,out} \\ \dot{Q}_i^{r,out} \end{bmatrix}$$

Why P and Q have been chosen as interface variables?

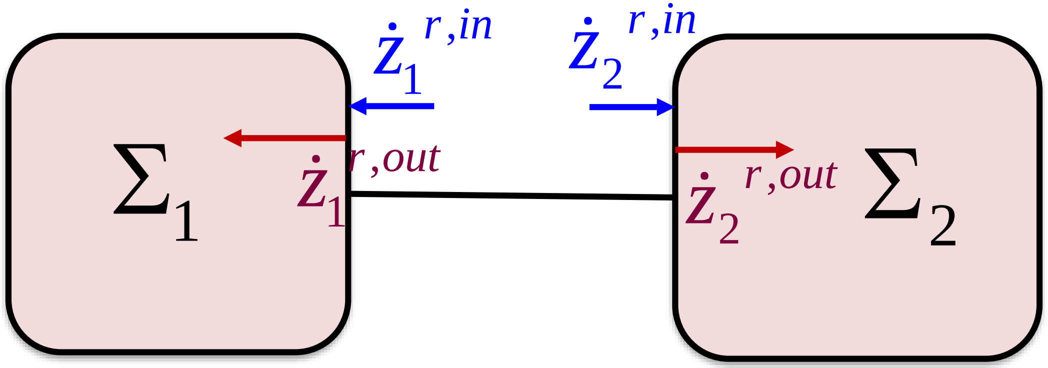
- P over a time quantifies useful work done
- Q at any time quantifies the associated inefficiencies in power transfer
- Both of them obey conservation laws at the interfaces

Representation of interactions within and across components

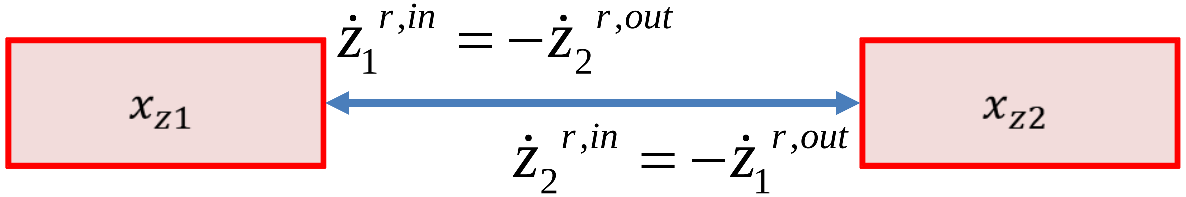
Zoomed-in representation:



Zoomed-out representation:



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



$$\dot{z}_1^{\,r,in} = -\dot{z}_2^{\,r,out}$$

$$\dot{z}_2^{\,r,in} = -\dot{z}_1^{\,r,out}$$

Distributed modular model

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

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

$$\begin{bmatrix} \dot{z}_1^{\,r,out} \\ \dot{z}_2^{\,r,out} \end{bmatrix} = \underbrace{\begin{bmatrix} 0 & -I_{2\times2} \\ -I_{2\times2} & 0 \end{bmatrix}}_{L_z}^{-1} \begin{bmatrix} \dot{z}_1^{\,r,in} \\ \dot{z}_2^{\,r,in} \end{bmatrix}$$

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

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

ODE model at interconnection level

$$\dot{\mathbf{x}}_{\mathbf{z}} = \underbrace{\begin{bmatrix} A_{z,1} & 0 \\ 0 & A_{z,2} \end{bmatrix}}_{\mathbf{A_z}} \mathbf{x_z} + \underbrace{\begin{bmatrix} B_t^{\,T} & B_t^{\,T} \end{bmatrix}}_{\mathbf{B_t}} \mathbf{E_t} + \begin{bmatrix} 0_{2\times2} & -I_{2\times2} \\ I_{2\times2} & 0_{2\times2} \end{bmatrix} \mathbf{z}^{\mathbf{r,in}}$$

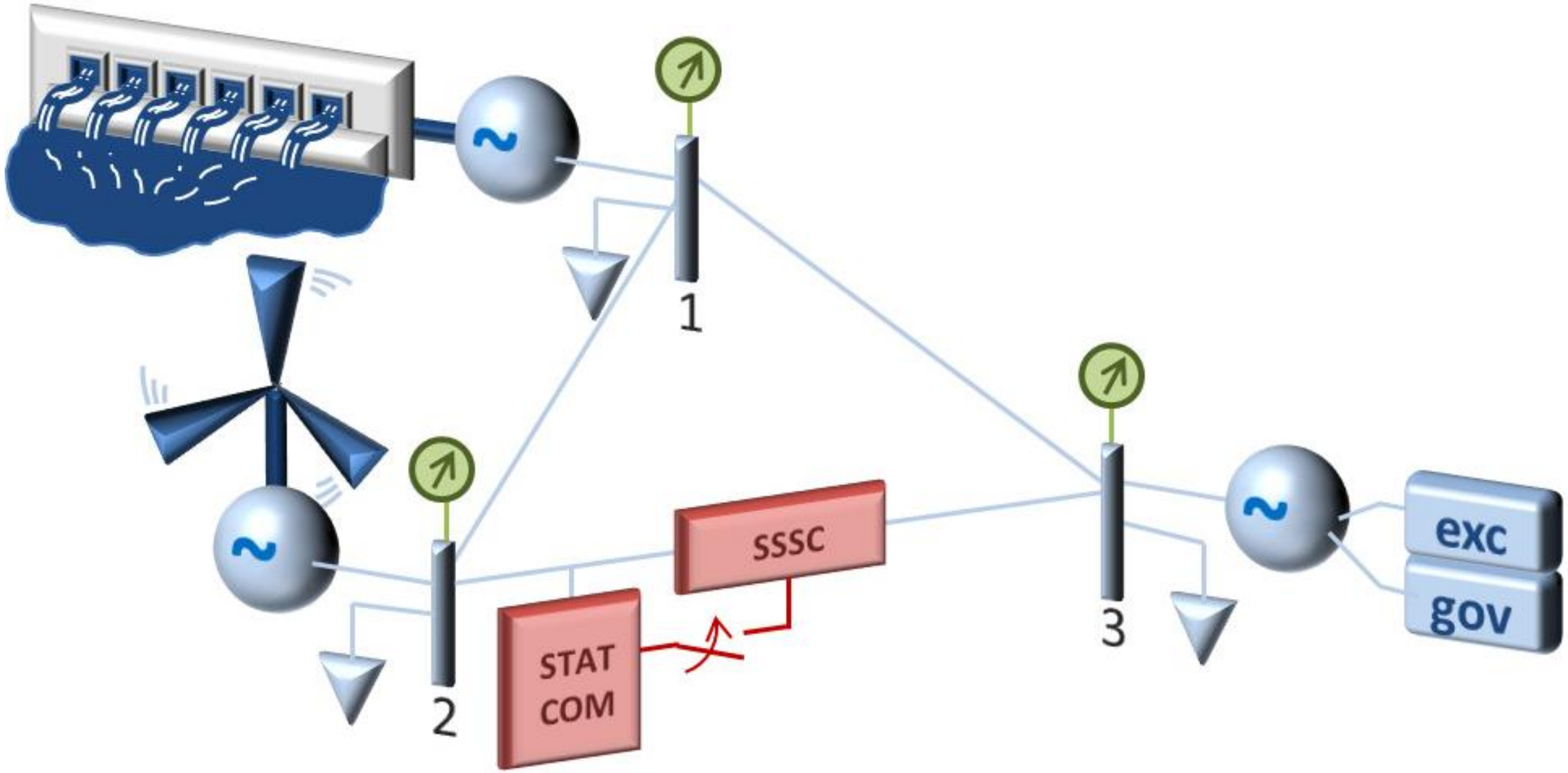
$$\mathbf{x_z} = \begin{bmatrix} x_{z,1} \\ x_{z,2} \end{bmatrix} \qquad \mathbf{E_t} = \begin{bmatrix} E_{t,1} \\ E_{t,2} \end{bmatrix} \qquad \dot{\mathbf{z}}^{\mathbf{r,in}} = \begin{bmatrix} \dot{z}_1^{\,r,in} \\ \dot{z}_2^{\,r,in} \end{bmatrix}$$

Potential of primary controllers: Challenge problem*

Challenge problem	State-of-the-art control primary control	Energy-based Plug-and-Play primary control (with microgrid control)
Case S1 (Sheriff, high load, low PV power)	Stable; does not settle to the right voltage w/o retuning; Induction motors when simulated result in poor voltage profile	Stable; voltage profile around 1 p.u. is ensured by generators re-adjusting their power output
Case S2.1 (Sheriff, islanded feeder1)	Stable; settles to right voltage if tertiary control set points are accurate. Dynamic loads when used result in poor voltage profile	Stable; voltage profile is good irrespective of the load model used.
Case S2.2 (Sheriff, islanded feeder 2)	Stable; Grid forming mode requires either lot of tuning or requires proper selection of filter parameters to ensure current evolves much faster than voltage. Switches might hit saturation for large disturbances.	Stable; Doesn't require any island detection loop for different modes of operation. Same control can be used in all the modes
Case S2.3 (Sheriff, islanded feeder3)	Stable; Short line model when used can result in over- voltage; Large in-rush current produced by Induction motors results in poor voltage profile	Stable; Regulates voltage irrespective of the line/load model
Case S3 (Sheriff, reconnecting)	Stable; but the load is not served; might also damage loads because of sudden drop in voltage; sensitive to control gains on generators and solar PV	Stable; desired load is always served as the generators reschedule themselves during sudden islanding and ensure good voltage profile with overshoots being within the protection limits

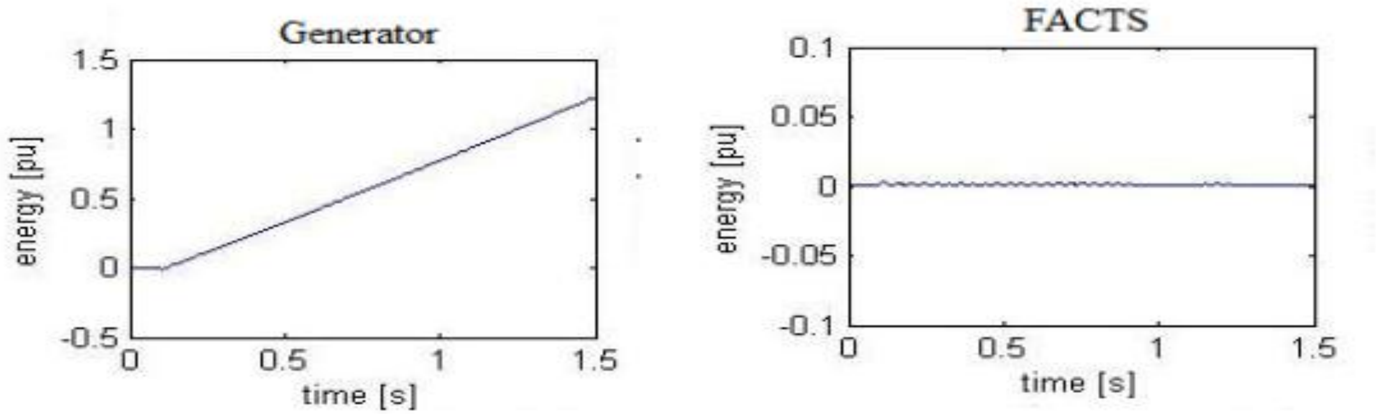
M.D. Ilic, Miao, X. and Jaddivada, R., "Plug-and-Play Reconfigurable Electric Power Microgrids," U.S. Patent 10,656,609, issued May 19, 2020.
Ilic, Marija D., Rupamathi Jaddivada, and Magnus Korpas. "Interactive protocols for distributed energy resource management systems (DERMS)." *IET Generation, Transmission & Distribution* 14, no. 11 (2020): 2065-2081.

Modeling principles for controlling systems with emerging technologies(renewable resources,DERs, wire control)

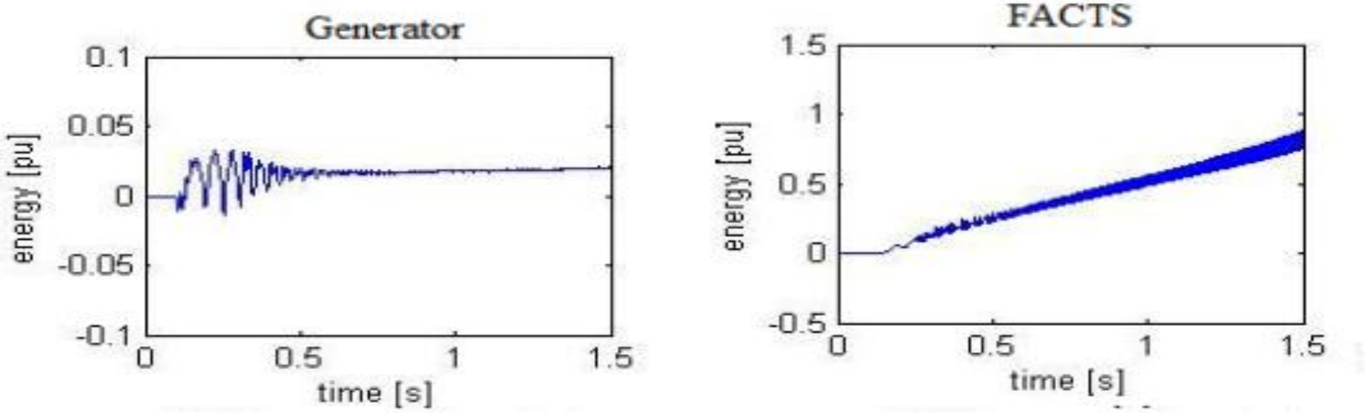


Cvetković, M., & Ilić, M. D. (2014). Ectropy-based nonlinear control of facts for transient stabilization. *IEEE Transactions on Power Systems*, *29*(6), 3012-3020.

The key idea: Control energy/power/rate of change of power



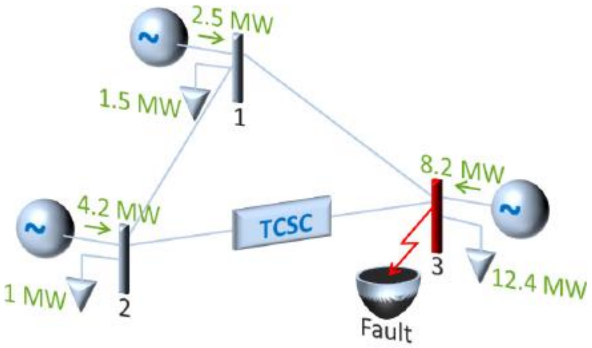
(a) Generator energy increment in an uncontrolled system (b) FACTS energy increment in an uncontrolled system

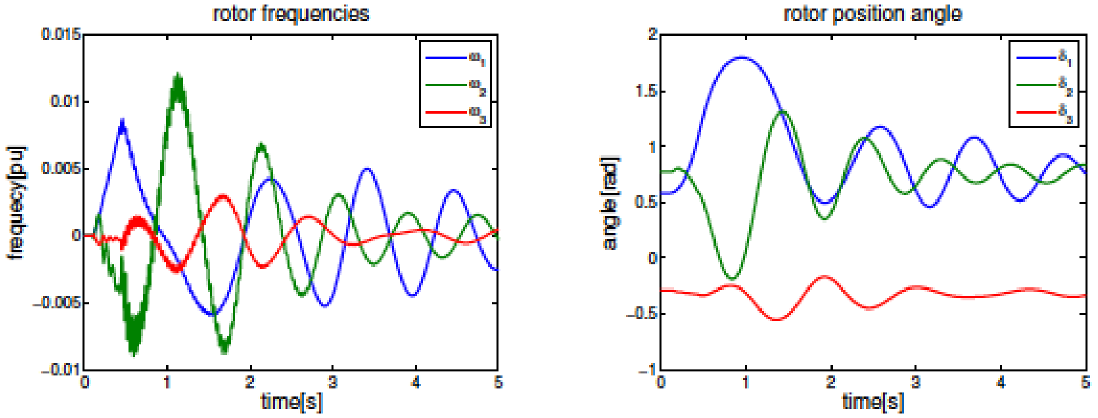


(c) Generator energy increment in a controlled system (d) FACTS energy increment in a controlled system

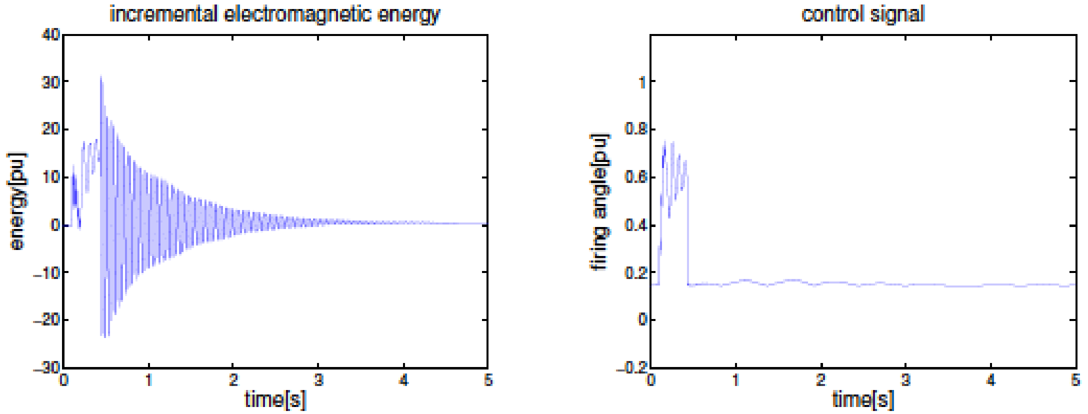
Increment of accumulated energy caused by a fault—the key role of FACTS control

Energy-based nonlinear FACTS control—huge opportunity



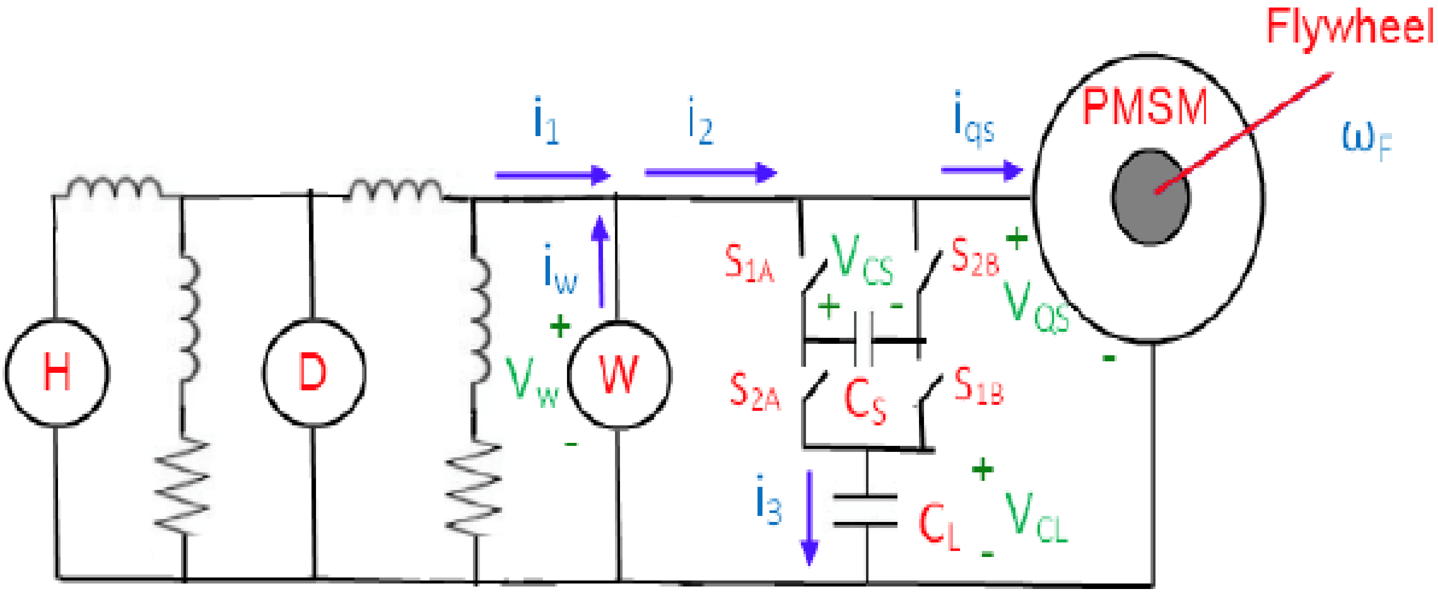


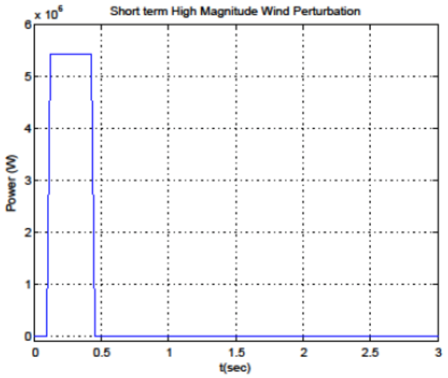
(a) Mechanical frequencies (b) Rotor position angles

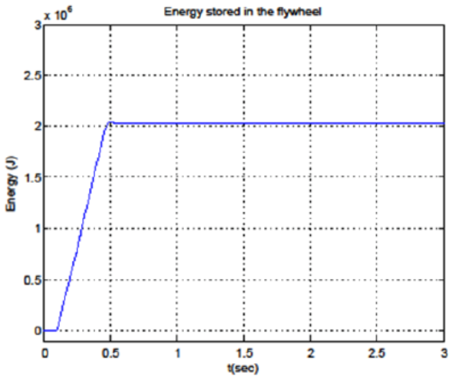


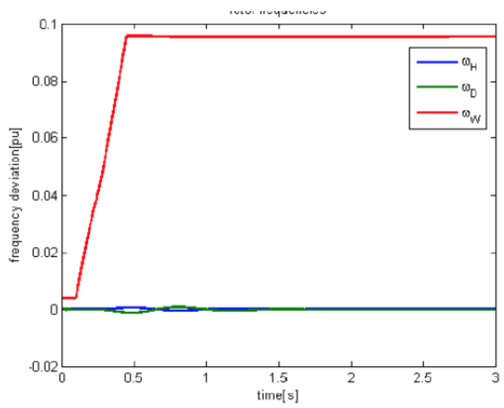
(c) Increment in accumulated energy (d) Controller signal

Potential of primary control for stabilizing prolonged effects of wind surges --flywheels





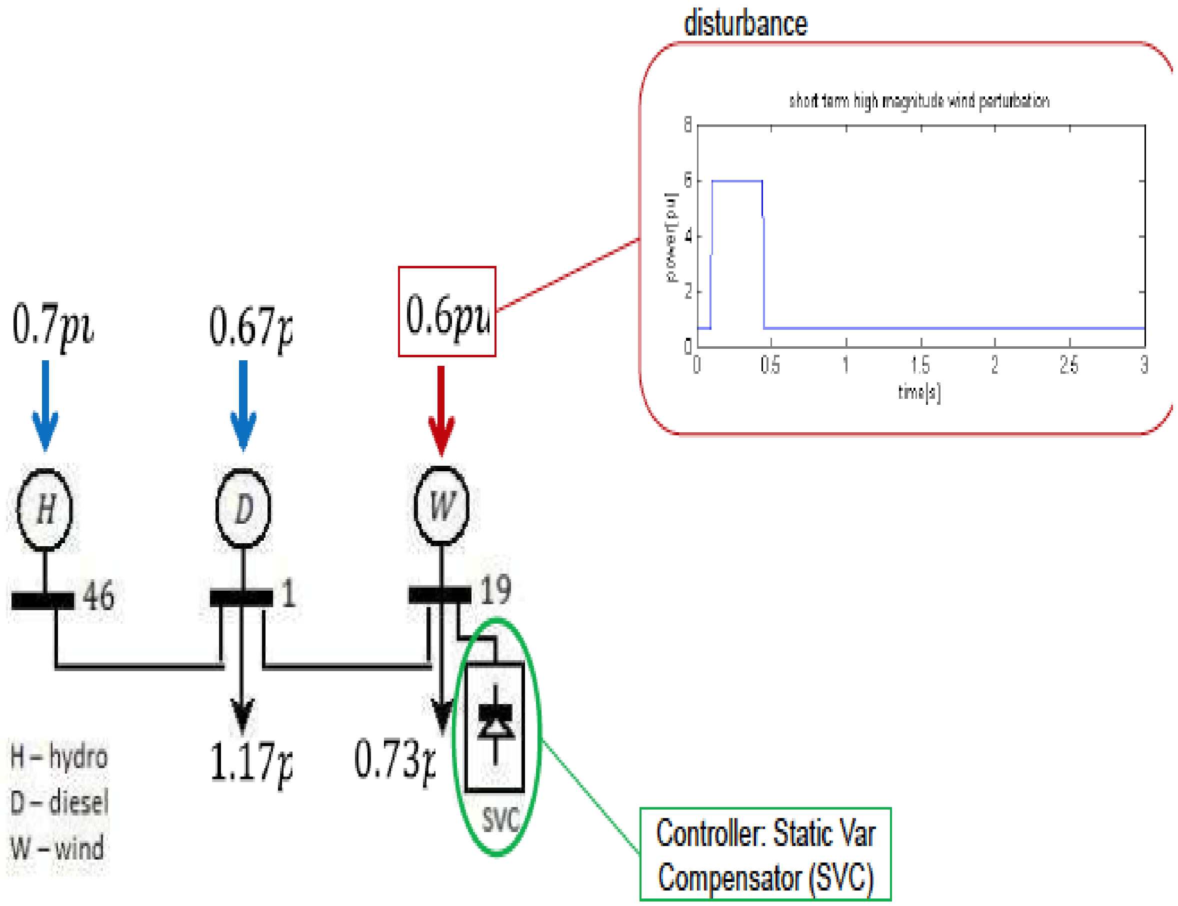




Ilić, M., Bachovchin, K., Cvetković, M., & Miao, X. (2014, December). Physics-based foundations for cyber and market design in complex electric energy systems. In *53rd IEEE Conference on Decision and Control* (pp. 4635-4654). IEEE.

High-gain switching stabilization for stabilizing short-term instabilities (huge potential of power electronics)

- High wind surges in Flores Island



Controller: Static Var Compensator (SVC)

Closing thoughts

- Necessary attributes (industry wish list) for operating and controlling future electric energy systems
- Availability* (supply-demand; new ways of doing it)
- Flexibility* (key role of control; must be provable, otherwise it does not work)
- Visibility, transparency* (data-enabled information exchange about functionalities)
- Simplicity** (modular, easy to deploy, utilize)

*Ken Mc Intyre, panelist DoE Transmission Innovation Summit, May 19,2021

**Greg Zweigle, SEL. panelist DoE Transmission Innovation Summit, May 19,2021

Looking forward

- Much room for innovation at value
- Digitalization for decarbonization; distributed interactive platforms; digital twins; ML/AI;
- Control implementation in complex nonlinear dynamical systems.
- Technology-agnostic principles for modeling, simulations and control
- Next generation software & control for changing industry

THANK YOU

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