Modeling and control of multi-energy dynamical systems: Hidden paths to decarbonization

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Presentation outline

- Emerging dynamical problems-roadblock to decarbonization
- Need to enhance today's practice; examples
- Proposed approach: Multi-layered energy modeling and control; from BAs to iBAs.
- Specifications for stand-alone subsystems; Feasibility and stability using energy dynamics.
- Physics-based minimal standards/ protocols for flexible utilization of diverse technologies over broad ranges of temporal and spatial conditions.

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; UFLS
  - Sporadic R&D under different modeling assumptions

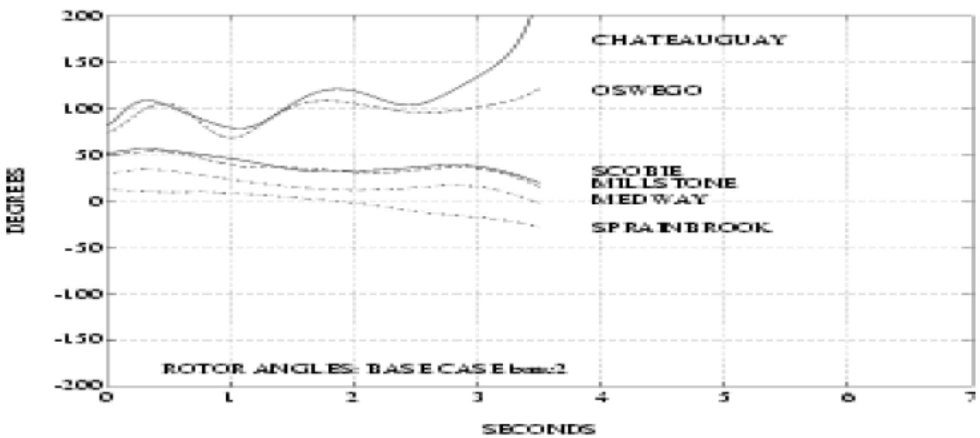
The NPCC .75Hz growing interarea oscillations

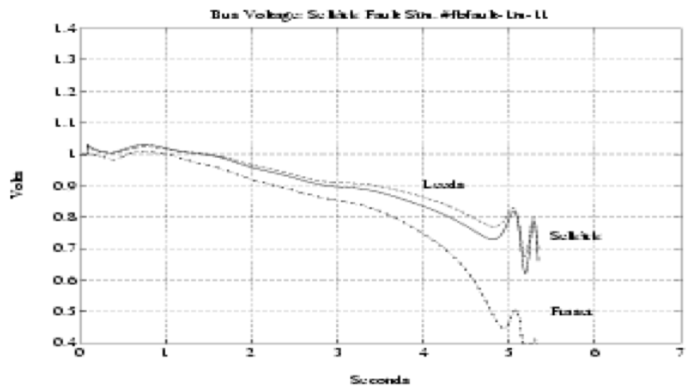
- A 38-bus, 29 machine equivalent dynamic model of the NPCC system
- It was shown to reproduce a multi-machine oscillation that occurred at .75Hz, involving groups of machines in NYC (modeled as Sprainbrook generator) and the northeastern part of New York State, as well as parts of Canadian power system (modelled primarily by the Oswego and Chateaguay units);
- The fault scenario selected for this test was a five-cycle three-phase short circuit of the Selkrik/Oswego transmission line carrying 1083MW. The oscillation grows until the Chateaguay generator loses synchronism, followed shortly by the Oswego unit.

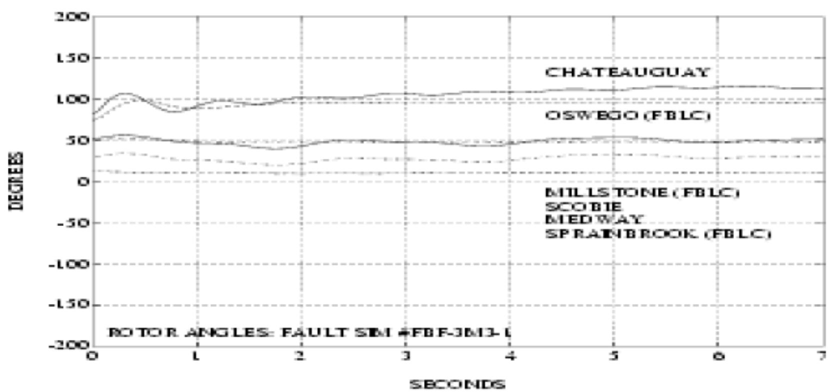
Chapman, J. W., Ilic, M. D., King, C. A., Eng, L., & Kaufman, H. (1993). Stabilizing a multimachine power system via decentralized feedback linearizing excitation control. IEEE Transactions on Power Systems, 8(3), 830-839.

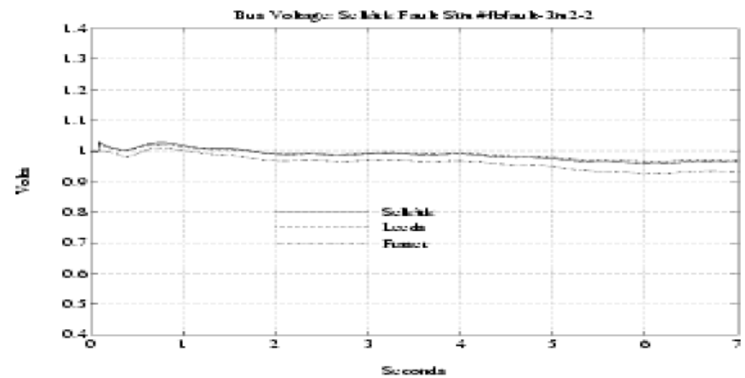
NY, NE and Canada islanding

Rotor angles -- base case for Selkrik fault



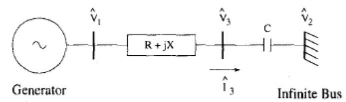




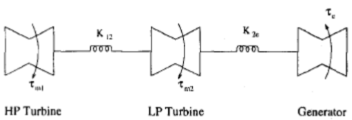


FBLC/SLIDING MODE CONTROL RESPONDS TO
RATE OF CHANGE OF POWER (ACCELERATION-RoCoF)

Torsional oscillations



i. Network for subsynchronous resonance simulation.



The torsional spring-mass model.

EIGENVALUES AND FREQUENCIES OF THE TORSIONAL STATE-SPACE SHAFT MODEL

Number(s)	Eigenvalue	Frequency (Hz)
1,2	$-0.07 \pm j196.54$	31.28
3,4	$-0.07 \pm j151.24$	24.07
5	0.00	–
6	-0.14	–

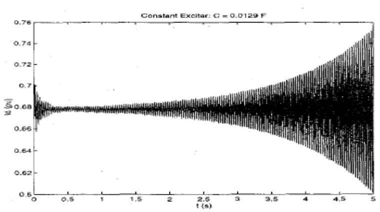


Fig. 16. Line current (real part of phasor) of a system experiencing subsynchronous resonance.

Compensation	Eigenvalue	Frequency (Hz)
2.96%	$-9.90 \pm j441.1$	70.20
	$-8.95 \pm j312.6$	49.75
	$-0.058 \pm j196.6$	31.29
	$-0.051 \pm j151.6$	24.13
	-34.84	–
	-30.90	–
	$-0.459 \pm j6.71$	1.07
	-4.88	
	-0.328	–
23.0%	$-10.41 \pm j557.4$	88.71
	$-7.95 \pm j196.1$	31.21
	$0.808 \pm j196.5$	31.27
	$0.061 \pm j152.2$	24.22
	-35.87	–
	-32.25	–
	$-0.644 \pm j7.65$	1.22
	-0.356	–
	-5.03	–
35.9%	$-10.55 \pm j602.7$	95.92
	$-0.053 \pm j196.4$	31.26
	$-9.35 \pm j151.7$	24.15
	$3.85 \pm j151.5$	24.11
	-36.79	–
	-33.60	–
	$-0.832 \pm j8.40$	1.34
	-0.378	–
	-5.14	–

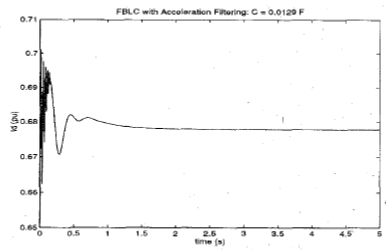


Fig. 19. Line current (real part of phasor) of a system with 23.0% compensation and FBLC with fourth-order Butterworth acceleration filtering.

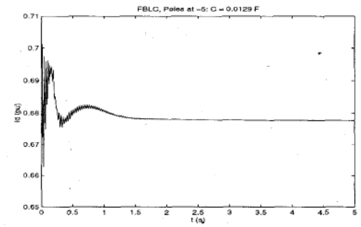


Fig. 17. Line current (real part of phasor) of a system with 23.0% compensation and FBLC.

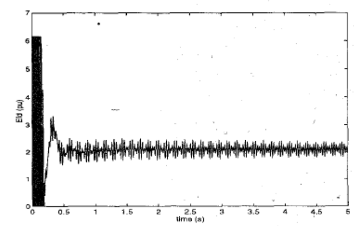


Fig. 20. Field voltage of a system with 23.0% compensation and FBLC with fourth-order Butterworth acceleration filtering.

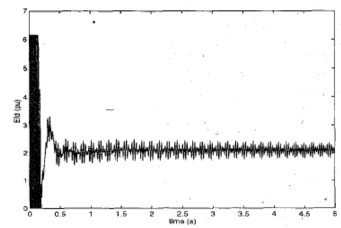


Fig. 20. Field voltage of a system with 23.0% compensation and FBLC with fourth-order Butterworth acceleration filtering.

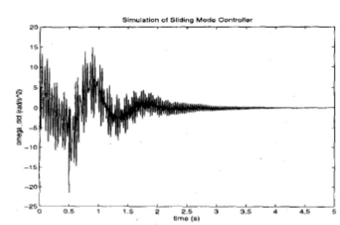


Fig. 29. Response of $\dot{\omega}$ to a 0.5 s fault with sliding control.

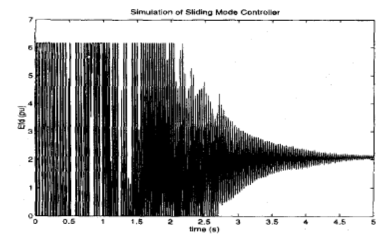


Fig. 30. Response of E_{fd} to a 0.5 s fault with sliding control.

****** Chapman, J. W., Ilic, M. D., King, C. A., Eng, L., & Kaufman, H. (1993). Stabilizing a multi-machine power system via decentralized feedback linearizing excitation control. IEEE Transactions on Power Systems, 8(3), 830-839.***

******* Allen, Eric H., Jeff W. Chapman, and Marija D. Ilic. "Effects of torsional dynamics on nonlinear generator control." IEEE transactions on control systems technology 4, no. 2 (1996): 125-140.***

State space transformation for rotating machines

- Conventional modeling

$$u_j = ri_j + \frac{d\psi_j}{dt}, \qquad j = 1, 2, \cdots, m$$

$$J\frac{d^2\theta}{dt^2} = T_e - T_l$$

$$T_j(\theta, i_j) = \frac{\partial W_j'}{\partial \theta}, \qquad j = 1, 2, \cdots, m$$

$$W_j'(\theta, i_j) = \int_0^{i_j} \psi_j(\theta, i_j)\, di_j.$$

$$\frac{dx}{dt} = f(x) + G(x)a(x) + G(x)S(x)v$$

$$\triangleq \tilde{f}(x) + \tilde{G}(x)v$$

$$\triangleq \tilde{f}(x) + \sum_{j=1}^{m} v_j(t)\tilde{g}_j(x)$$

- Transformed state space

$$y = (\theta, \omega, \alpha, i_1, \cdots, i_{k-1}, i_{k+1}, \cdots i_m)$$

$$= \Phi(\theta, \omega, i_1, \cdots, i_m)$$

$$\alpha = \frac{d\omega}{dt} = \frac{1}{J}\left\{\sum_{j=1}^{m} T_j(\theta, i_j) - T_l(\theta, \omega)\right\}.$$

$$\frac{d\theta}{dt} = \omega$$

$$\frac{d\omega}{dt} = \alpha$$

$$\frac{d\alpha}{dt} = v_k$$

$$\frac{di_j}{dt} = v_j, \qquad j \neq k, j = 1, 2, \cdots, m$$

$$u_j = ri_j + \frac{\partial \psi_j}{\partial \theta}\omega + \frac{\partial \psi_j}{\partial i_j} v_j, \qquad j \neq k, j = 1, 2, \cdots, m$$

$$u_k = ri_k + \frac{\partial \psi_k}{\partial \theta}\omega + \frac{\partial \psi_k}{\partial i_k}\left(\frac{\partial T_k}{\partial i_k}\right)^{-1} \cdot \left[Jv_k + \frac{dT_l}{dt} - \sum_{j=1}^{m}\frac{\partial T_j}{\partial \theta}\omega - \sum_{\substack{j=1 \\ j\neq k}}^{m}\frac{\partial T_j}{\partial i_j}v_j\right].$$

- Feedback linearizing control for stand-alone SRM
- Closed-loop model lends itself to provable control of torque dynamics

Ilic, M., Marino, R., Peresada, S., & Taylor, D. (1987). Feedback linearizing control of switched reluctance motors. IEEE Transactions on Automatic Control, 32(5), 371-379.

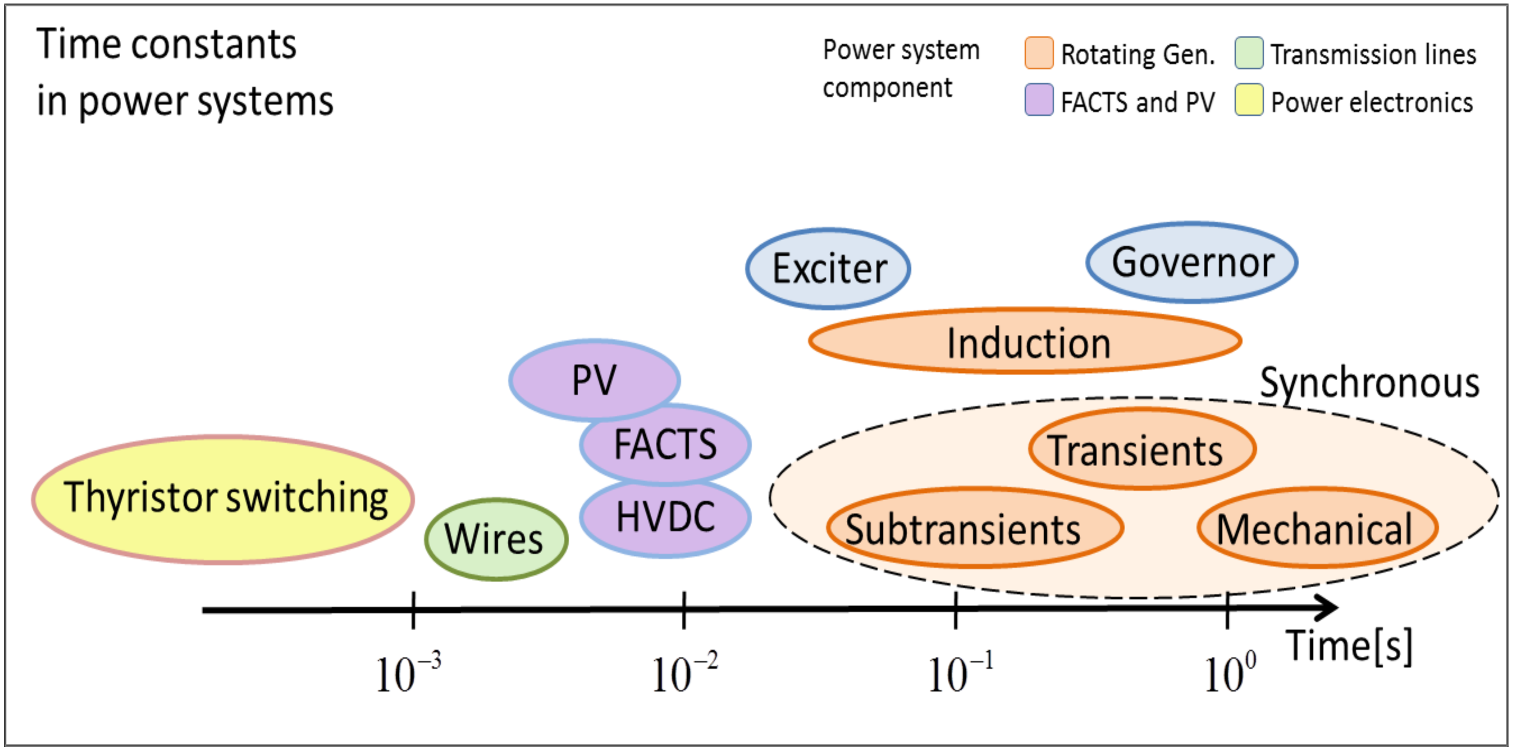
Hidden problems in today's primary controllers

- Governor (output feedback; not guaranteed to be stable)
- AVR (designed for controlling voltage magnitude –nonlinear function of states; no guaranteed stability due to linearization)
- PSS --- full state PID controller (voltage cannot be controlled over broad ranges of system conditions due to linearization)
- Feedback linearizing control (FBLC) – enhanced PSS (works over broader ranges of system conditions; voltage problematic; non robust wrt model/sensing uncertainties)
- Sliding mode control (SMC) –brings robustness to FBLC; excellent application of power electronics

R&D on control of electromechanical interactions

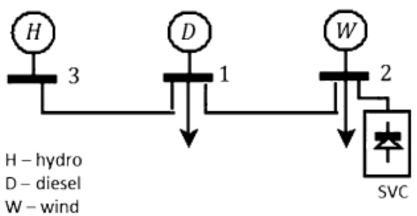
- Torsional oscillations; low frequency oscillations during faults
- Key idea-– control rate of electrical power
- No linearization—feedback linearizing control/sliding mode control to make dynamics of electrical power stable in closed loop
- The first use of FBLC in interconnected power systems; interpretation in transformed state space (power – rate of change of stored energy—intVar)
- Demonstration on NY real world data; in collaboration with industry

New control equipment/new modeling and primary control challenge-fast electromagnetic problems



Transient stabilization in systems with wind power –SVC

Potential of Nonlinear Fast Power-Electronically-Switched Storage



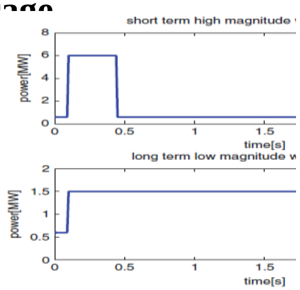


Fig. 19.2 Wind disturbances simulated in the Flores exar

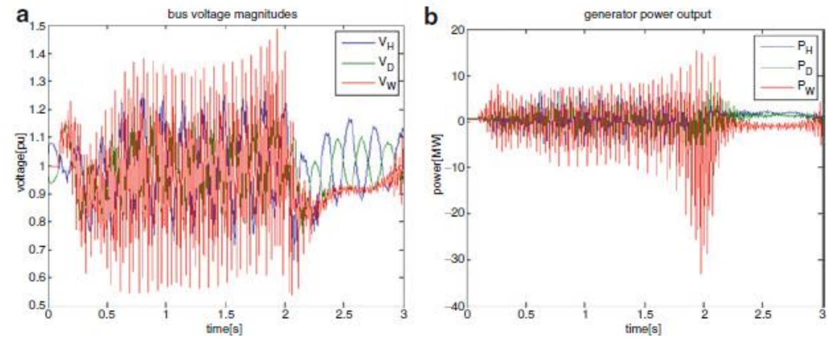


Fig. 19.14 (a) Voltage on the buses and (b) the electric power output of the generators if the system is controlled by the proposed energy-based controller

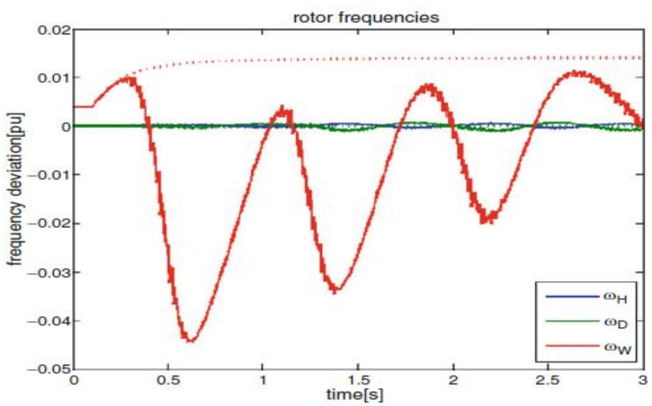


Fig. 19.16 Mechanical frequency of all generators in the system during a long-term low-magnitude wind perturbation: (a) *dashed* (without control on the SVC), (b) *solid* (with control on the SVC)

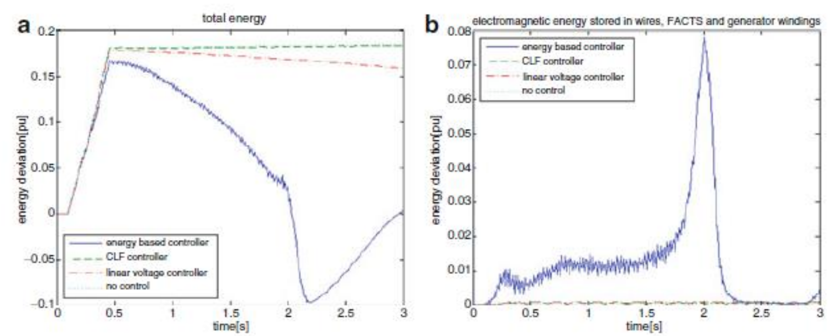
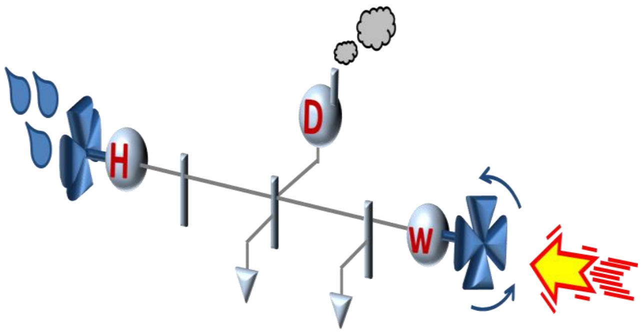


Fig. 19.15 (a) Total accumulated energy and (b) total accumulated electromagnetic energy in a system controlled by different controllers

Oscillations in islands –prolonged wind gusts



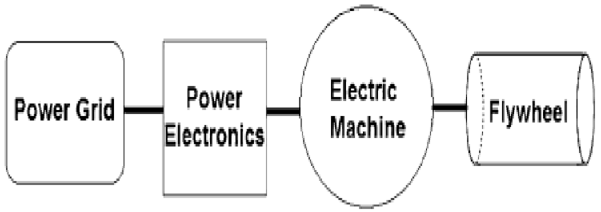


Fig. 19.20 Interface between the power grid and the flywheel

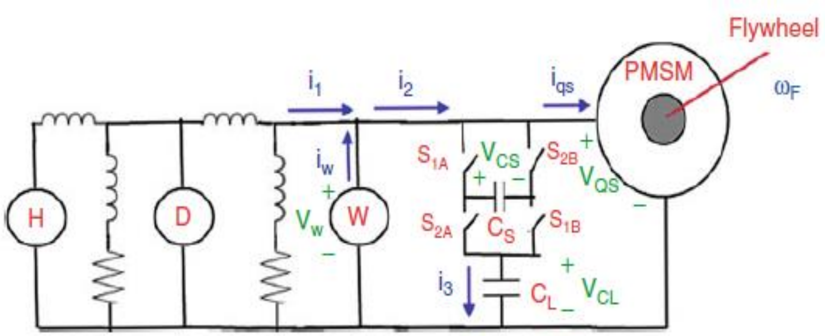


Fig. 19.34 Full diagram connecting the flywheel to Flores

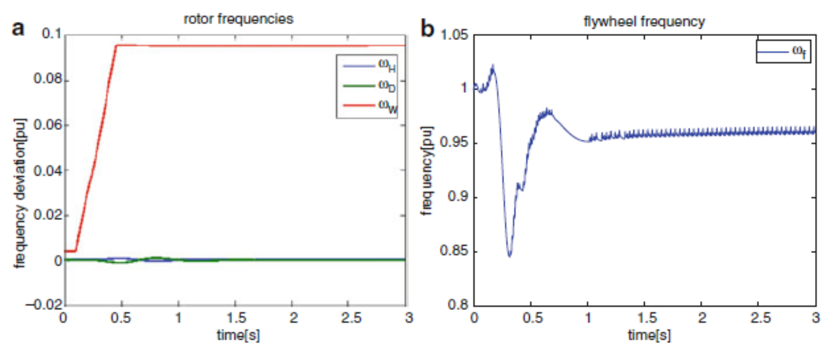
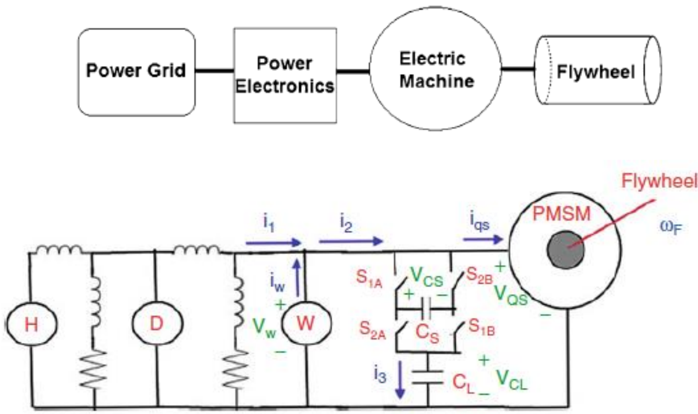


Fig. 19.35 Frequency of (a) the hydro, diesel, and wind generators, and (b) the flywheel, in the Flores system

Transient stabilization with flywheels

Concept of Sliding Mode Control Applied to a Flywheel



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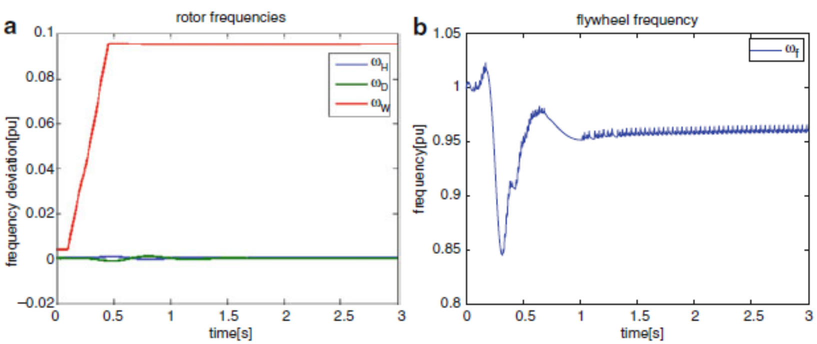

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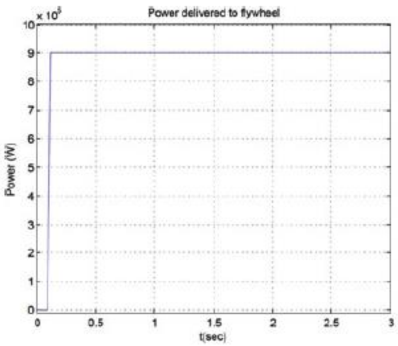
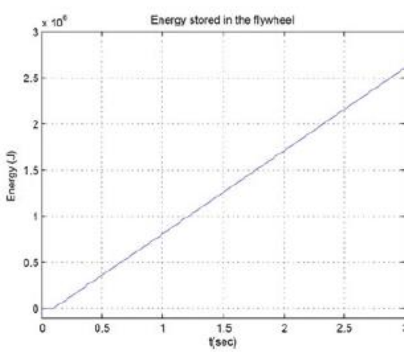


Fig. 19.32 Power delivered to the flywheel in r



Hindsight view of FBLC and SMC

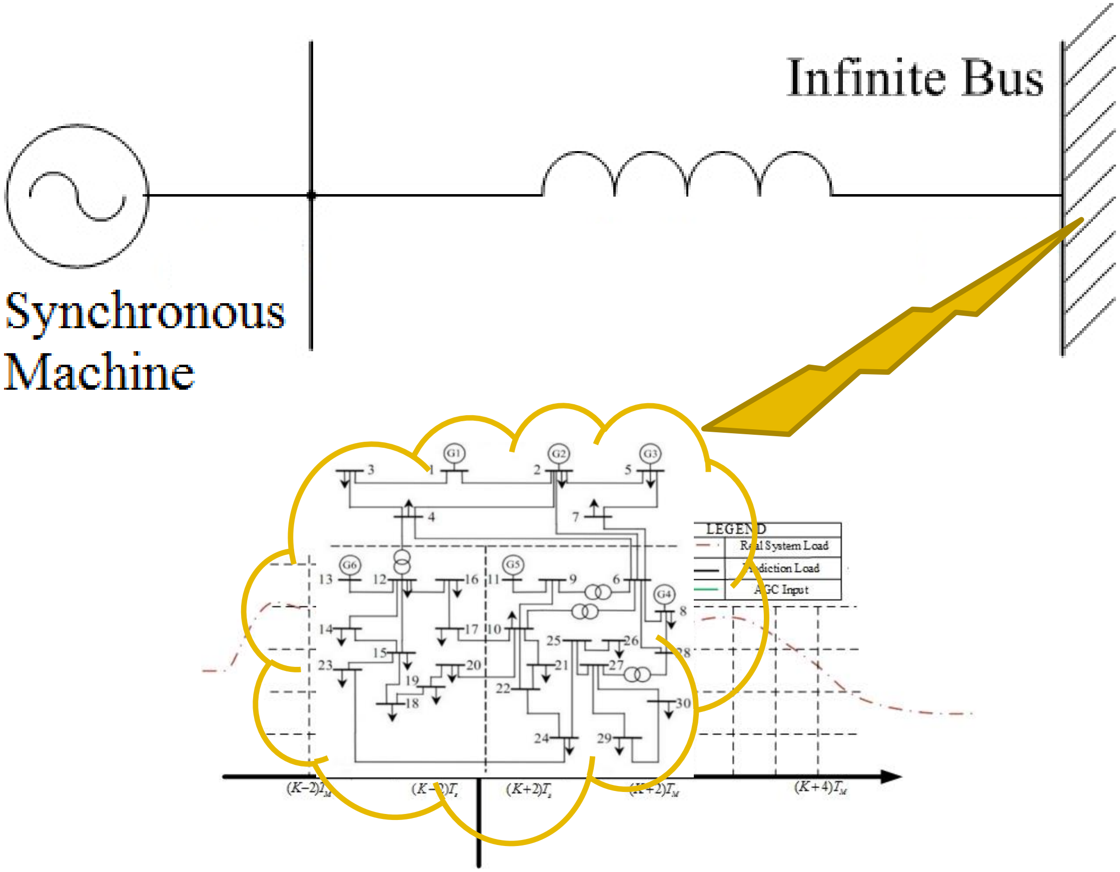
- NY .7Hz oscillation controlled by a nonlinear power system stabilizer (PSS) which works over broad ranges of operations (nuclear power plant outage)
- Field exciter responds to the rate of change of power to ensure response of frequency
- FACTS, flywheels, SVC – all respond to the rate of change of electromagnetic energy and are controlled by fast power electronics switching

- **TODAY's DECENTRALIZED, LINEARIZED OUTPUT FEEDBACK CONTROLLERS CANNOT STABIIZE SYSTEM DYNAMICS (FREQUENCY AND/OR VOLTAGE)**
- **KEY ROLE OF CONTROLLING RATE OF CHANGE OF POWER**
- **KEY NOTION OF INTERACTION VARIABLE (CLOSELY RELATED TO RATE OF CHANGE OF POWER); LEAD TO ENERGY DYNAMICS AND CONTROL**

Enhancements needed—hidden traps

- ***A (tertiary level controller*)**: should have adaptive performance metrics and optimize over all controllable equipment *(not today)*
- ***B (secondary control-droops):*** *modeling often hard to justify (droops only valid in 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!*
- *Control co-design key to improved performance*

Today's industry practice—tune generator control



Time-scales of frequency and voltage control

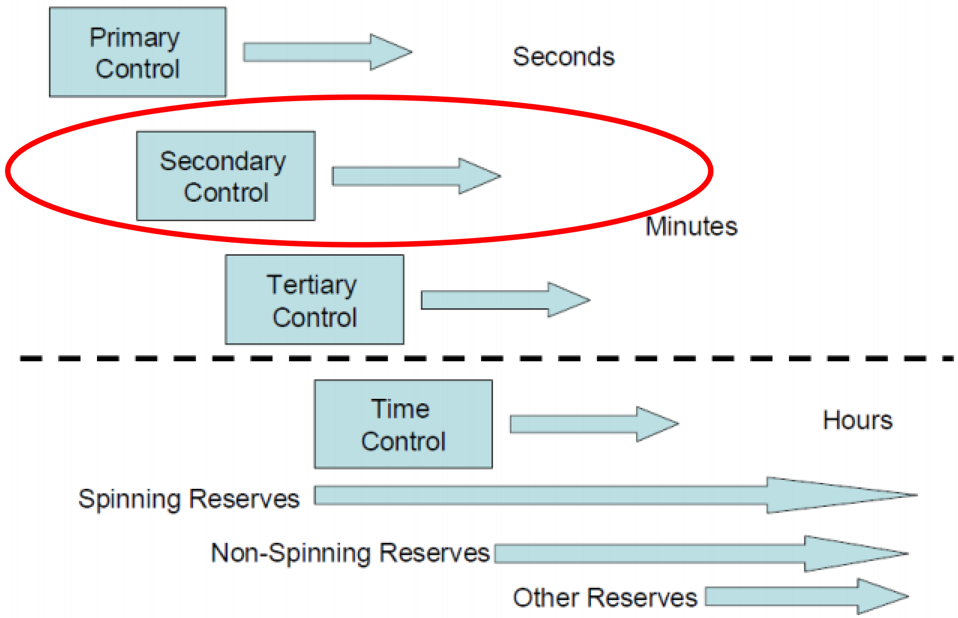
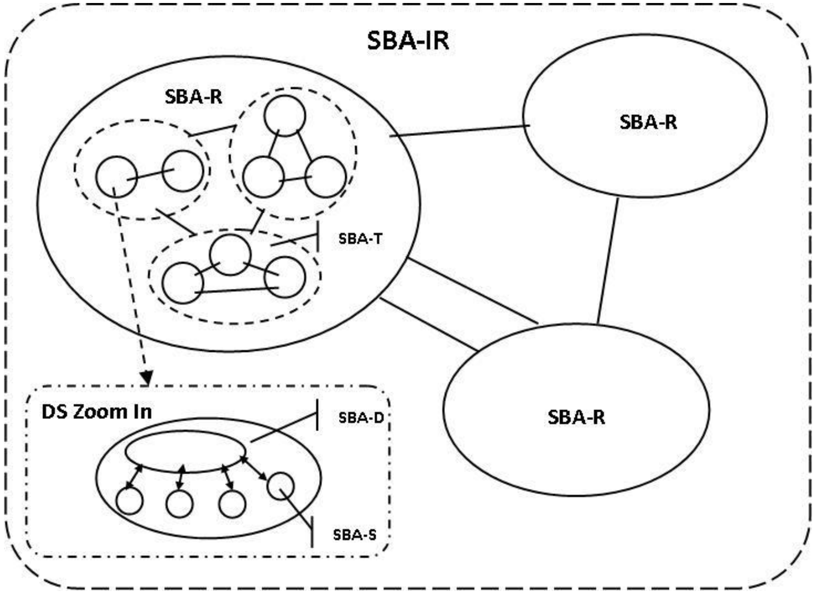


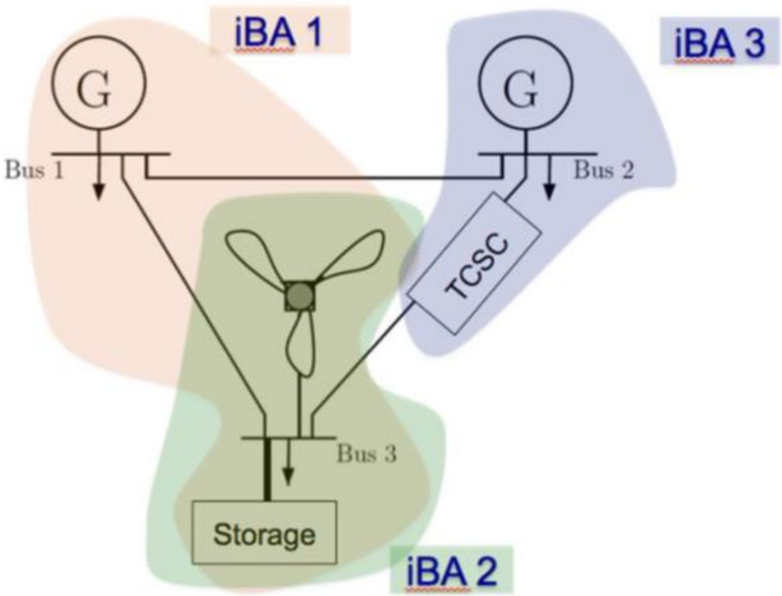
Figure 6. Control Continuum

Source: “Balancing and Frequency Control,” NERC Resources Subcommittee, 2011

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

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





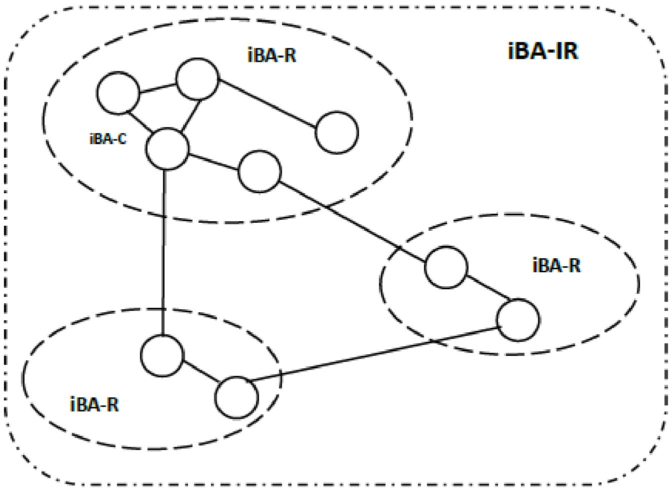
Note: SBAs renamed to iBAs (suggestion by a PSERC member some time ago)

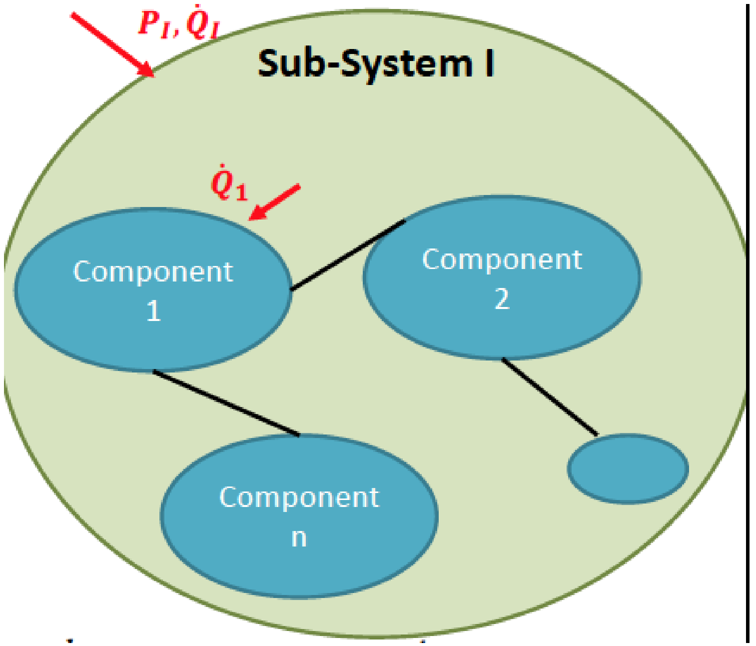
Ilic, M., "Dynamic Monitoring and Decision Systems for Enabling Sustainable Energy Services", Network Engineering for Meeting the Energy and Environmental Dream, Scanning the Issue, Proc. of the IEEE,2011.

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)

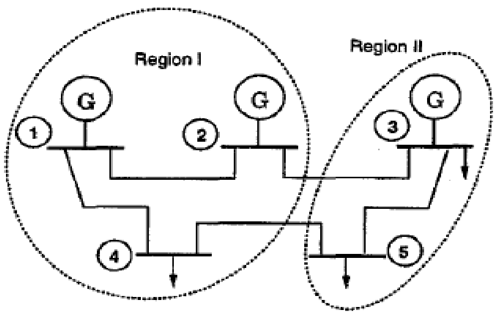
Innovation time line (1990s-2020's) – Energy modeling using intVars

- Introduced in an increasing order of complexity
- Linear frequency dynamics in transformed state space*
- Used to formalize LQR for hierarchical frequency modeling and control (time scale separation assumed)**
- Time scale separation relaxed***; needed for controlling frequency in systems with intermittent resources (ODEs)
- Nonlinear control of torsional oscillations****
- More recent generalization to include coupled nonlinear electromechanical-electromagnetic dynamics***** (non-standard form of ODEs)
- Critically relevant for distributed nonlinear control of faults, wind gusts, equipment loss, reconfigurations; huge opportunity for power electronics

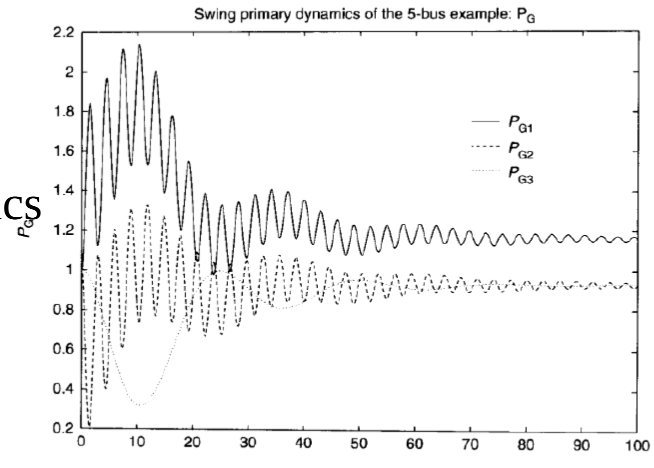
*Ilic, M. and Liu, X., 1994. A simple structural approach to modeling and control of the inter-area dynamics of the large electric power systems: Part ii nonlinear models of frequency and voltage dynamics. NAPS Proceedings.
**Ilic, Marija, X. Liu, B. Eidson, C. Vialas, and Michael Athans. ”A structure-based modeling and control of electric power systems.” Automatica 33, no. 4 (1997): 515-531.
***Ilic, Marija D., and Qixing Liu. ”Toward sensing, communications and control architectures for frequency regulation in systems with highly variable resources.” In Control and optimization methods for electric smart grids, pp. 3-33. Springer, New York, NY, 2012.
****

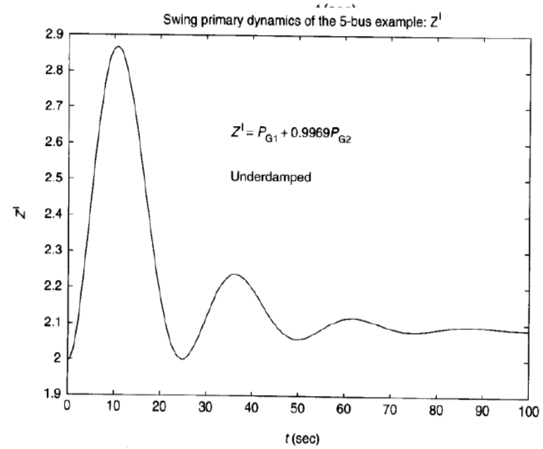
Inter-area dynamics- interaction variable

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



Local/internal dynamics





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

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

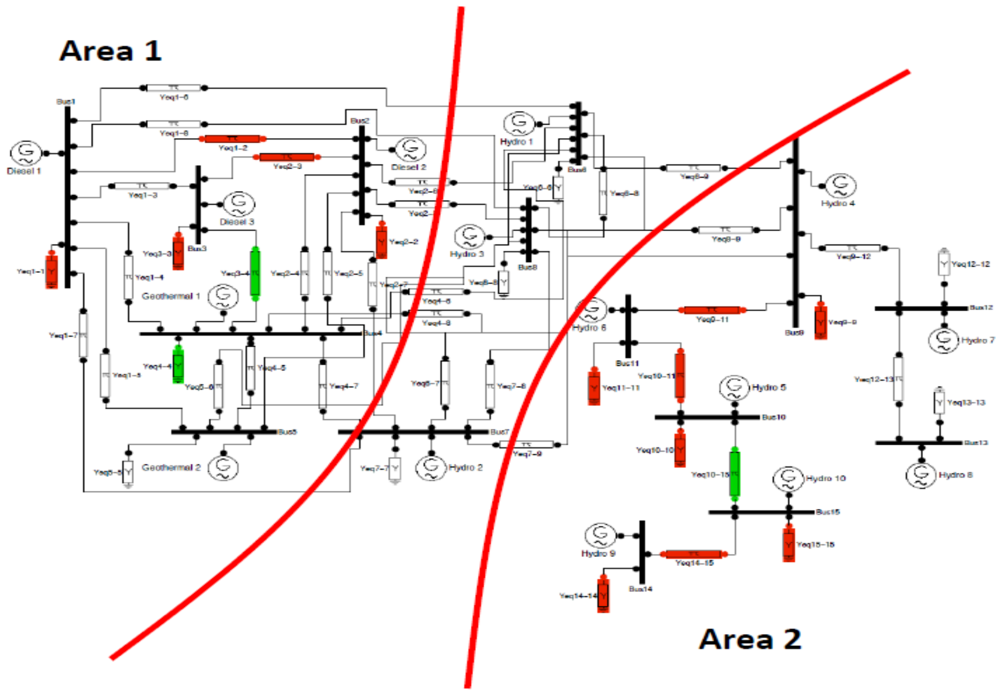
when all interconnections among the subsystems S^i, $i = \text{I}, \ldots, R$ are removed, and the system is free of disturbances.

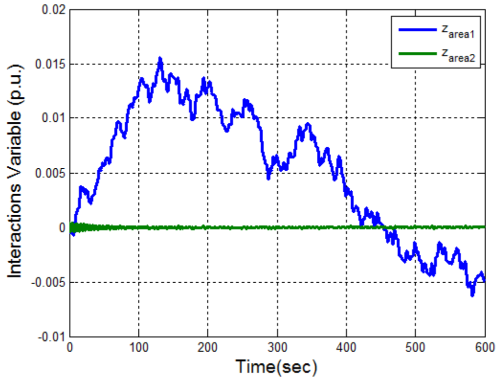
$$z^i(t) = P^i x^i(t), \qquad i = \text{I}, \text{II}, \cdots \tag{6.122}$$

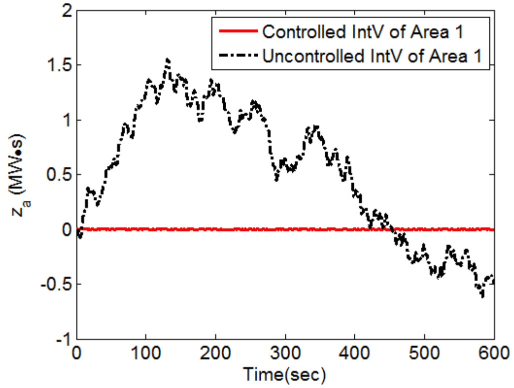
$$z^i(t) = p^i P_G^i \tag{6.131}$$

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.

Dynamics of interaction variables of two areas—Sao Miguel



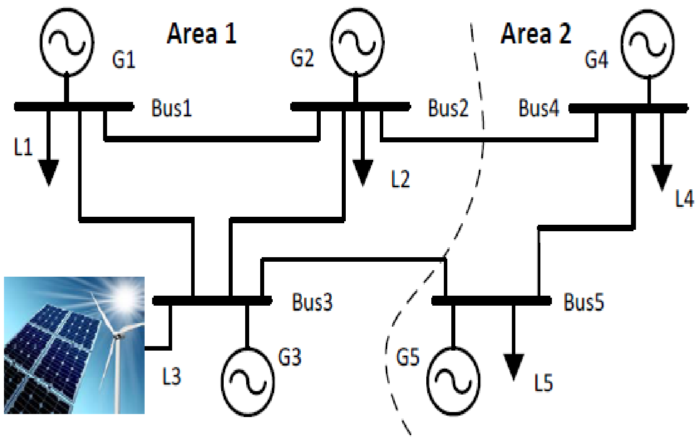


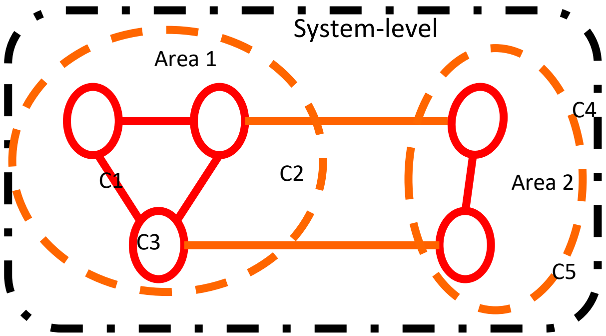


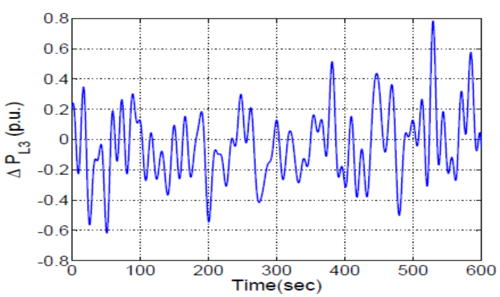
IntVar of area 1—sum of generation-load deviations in Area 1 around dispatch (power flow);
IntVar of area 2—sum of generation-load deviations in Area 2 around dispatch (power flow)

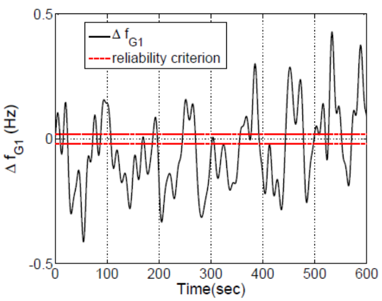
Ilic, M., Xie, L., & Liu, Q. (Eds.). (2013). *Engineering IT-enabled sustainable electricity services: the tale of two low-cost green Azores Islands* (Vol. 30). Springer Science & Business Media.

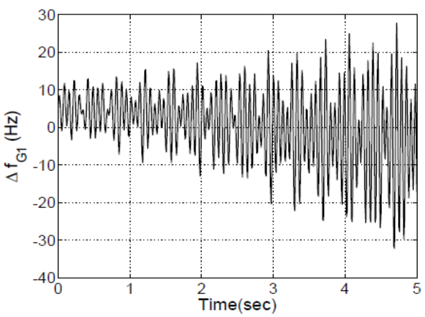
A large-scale systems framework for coordinated frequency control with intermittent disturbances –new relevance





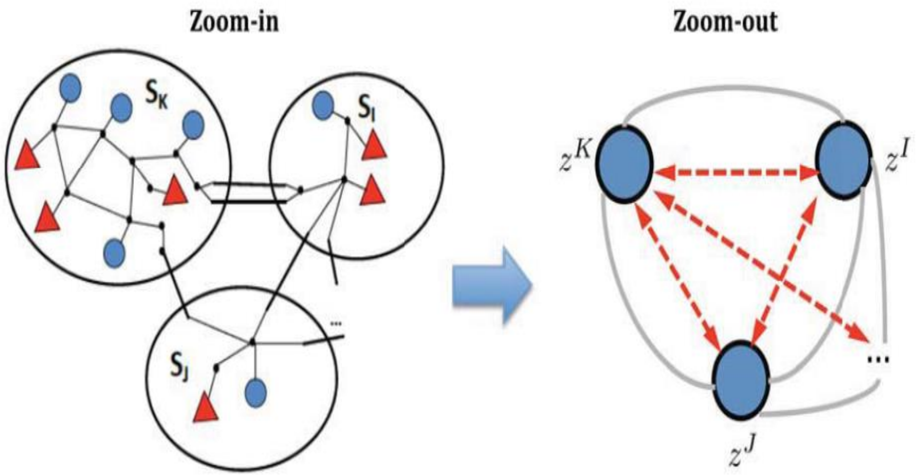


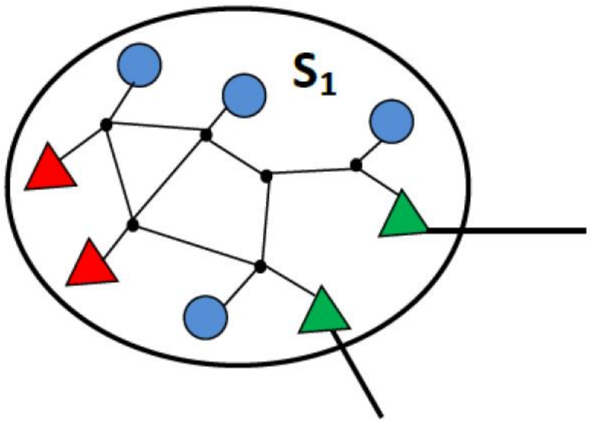


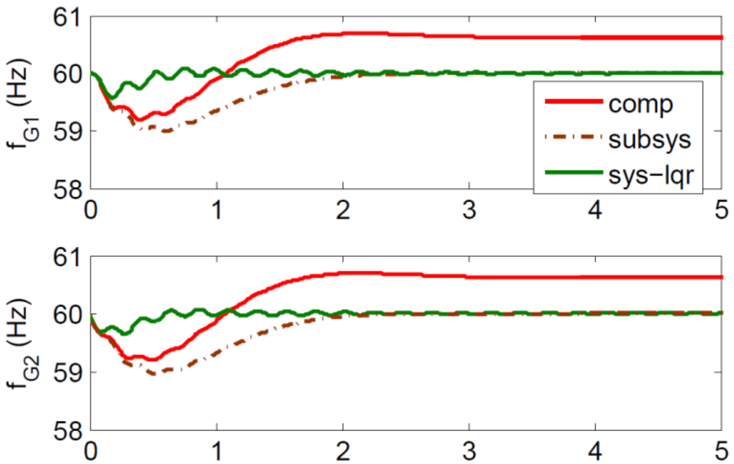


CONTINUOUS POWER FLUCTUATIONS AND OPERATING PROBLEMS (POOR FREQUENCY QUALITY, INSTABILITIES)

Frequency stabilization using intVar

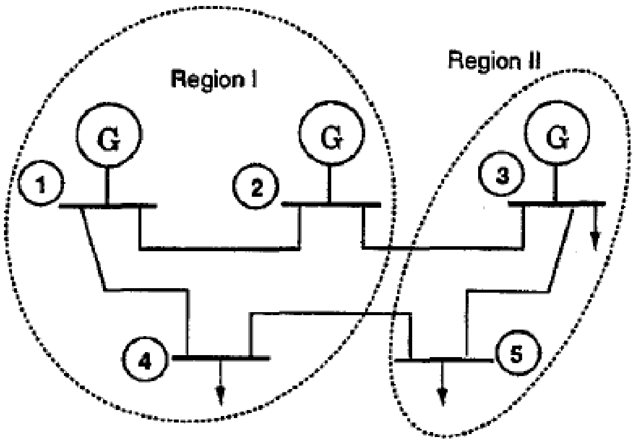






- Dependence of frequency response on power balancing control (generator , BA level, system levels)
- Use of intVars makes these scalable

Basics on intVar: transformed state space (v.1)



$$M\dot{\omega}_G + D\omega_G = P_{ta} + e_T a - P_G$$

$$T_u \dot{P}_{ta} = -P_{ta} + K_t a$$

$$T_g \dot{a} = -ra - \omega_G + \omega_G^{ref}$$

$$\dot{x}_{LC} = \begin{bmatrix} -D/M & 1/M & e_T/M \\ 0 & -1/T_u & K_t/T_u \\ -1/T_g & 0 & -r/T_g \end{bmatrix} x_{LC} + \begin{bmatrix} -1/M \\ 0 \\ 0 \end{bmatrix} P_G$$

$$F_G + P_G = J_{GG}\delta_G + J_{GL}\delta_L$$

$$F_L - P_L = J_{LG}\delta_G + J_{LL}\delta_L$$

$$\dot{P}_G = K_P \omega_G + \dot{F}_e - D_P \dot{P}_L$$

$$y^i = p^i P_G^i = \sum_{j=1}^{n_G^i} P_{Gj}^i = \text{total generation of area } i$$

$$\dot{y} = p(\dot{F}_e - D_P \dot{P}_L)$$

$$\begin{bmatrix} \dot{x}_{LC} \\ \dot{P}_G \end{bmatrix} = \begin{bmatrix} A_{LC} & C_M \\ K_P E & 0 \end{bmatrix} \begin{bmatrix} x_{LC} \\ P_G \end{bmatrix} + \begin{bmatrix} 0 \\ \dot{F}_e \end{bmatrix} + \begin{bmatrix} 0 \\ -D_P \end{bmatrix} \dot{P}_L$$

Ilic, M., Liu,X., ``A Simple Structural Approach to Modeling and Analysis of the Inter-area Dynamics of the Large Electric Power Systems: Part I - Linearized Models of Frequency Dynamics, Proc NAPS, 1994.

Use of intVar for distributed control

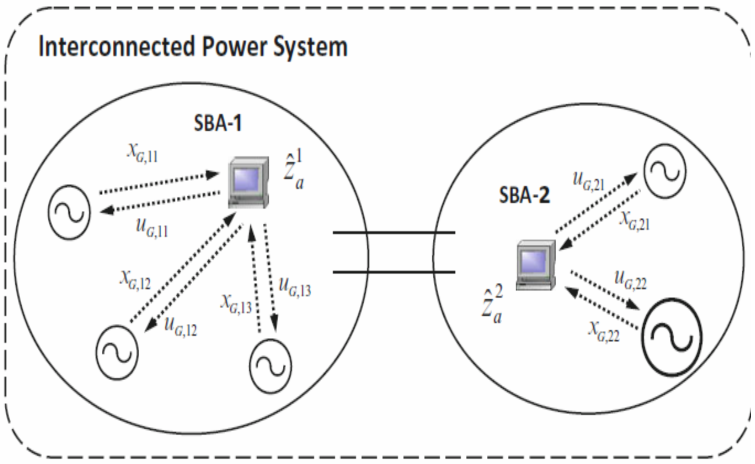


Fig. 5 The communication scheme of the E-AGC system in the weak interaction scenario

$$\underset{\hat{u}}{\text{minimize}} \quad J = \frac{1}{2}\int_0^\infty \left[\hat{y}^T Q\hat{y} + \hat{u}^T R\hat{u}\right] \mathrm{d}t$$

$$\text{subject to} \quad \frac{\mathrm{d}\hat{x}}{\mathrm{d}t} = \hat{A}\hat{x} + \hat{B}\hat{u}$$

$$\hat{y} = \hat{C}\hat{x}$$

$$\hat{u} = -\hat{K}\hat{y}.$$

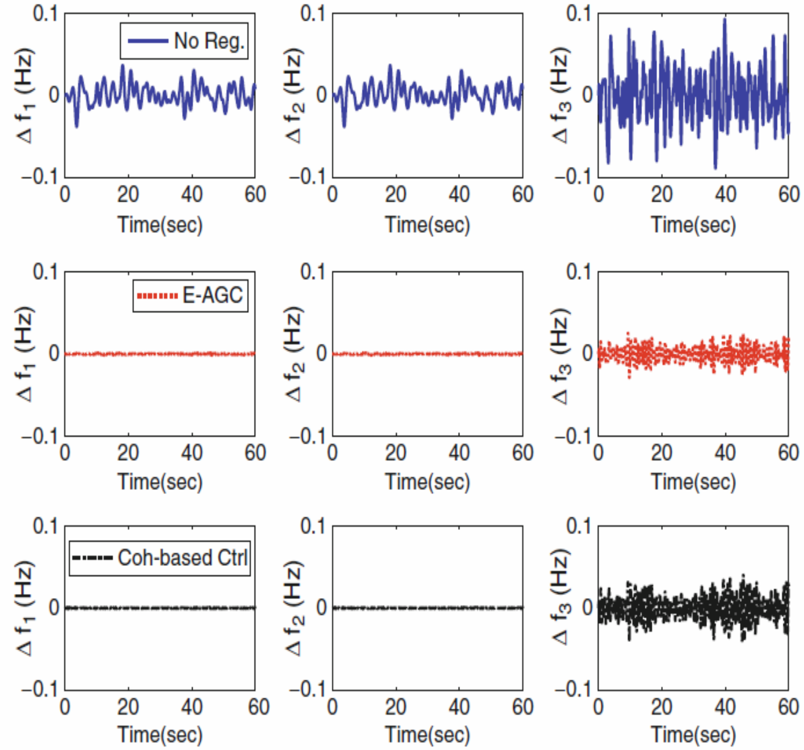


Fig. 8 System frequency performance for case 1

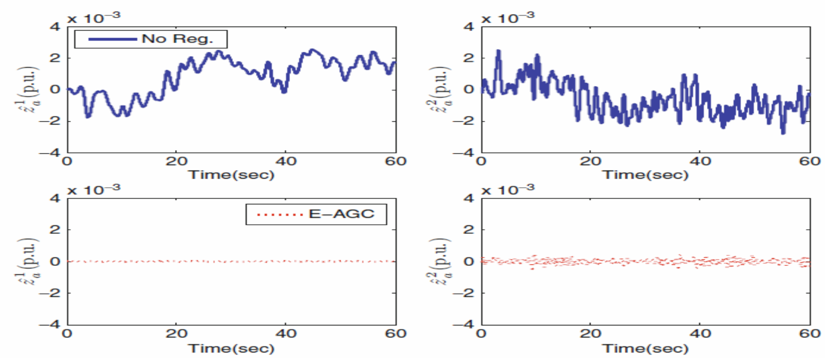
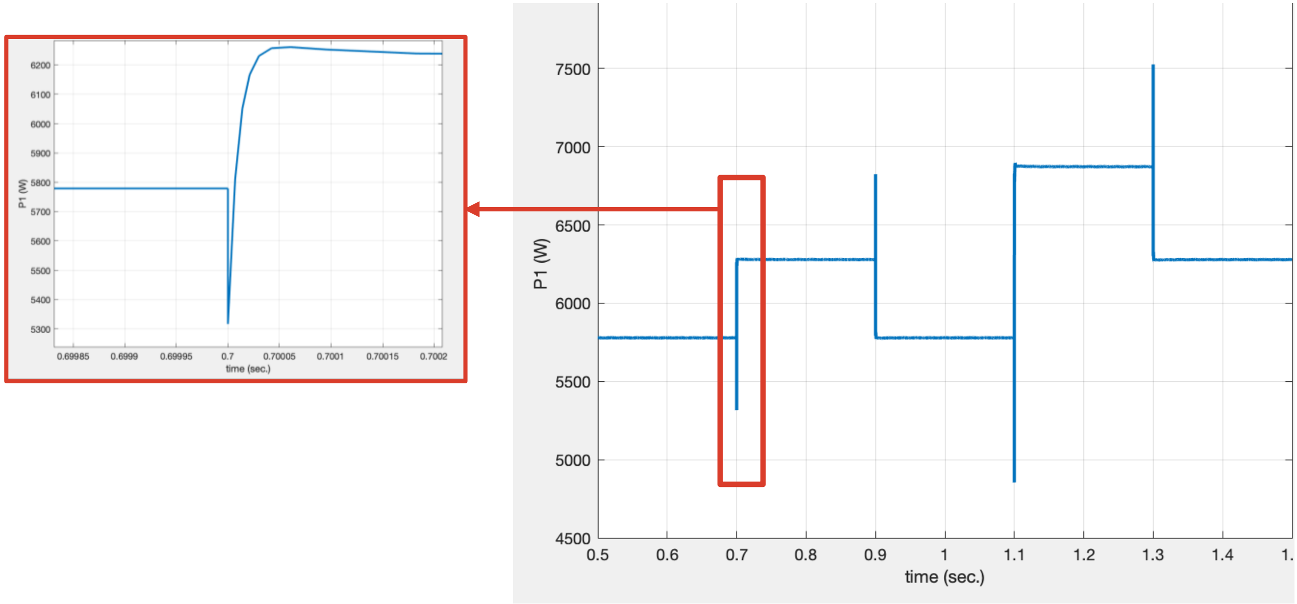
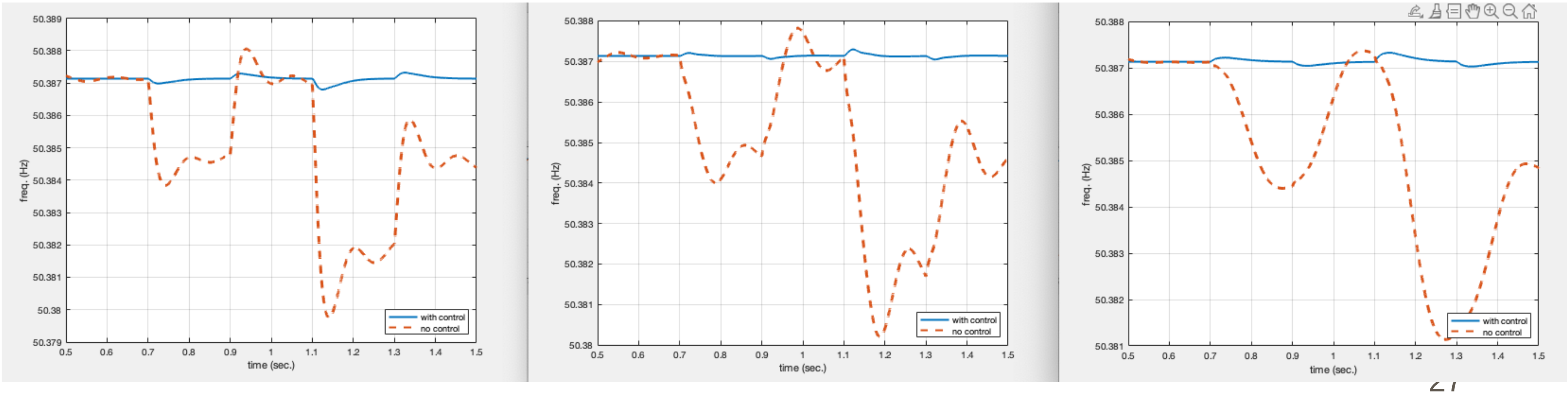


Fig. 12 System interactions variable performance for case 1

Ilić, Marija D., and Qixing Liu. "Toward sensing, communications and control architectures for frequency regulation in systems with highly variable resources." *Control and optimization methods for electric smart grids*. Springer, New York, NY, 2012. 3-33.

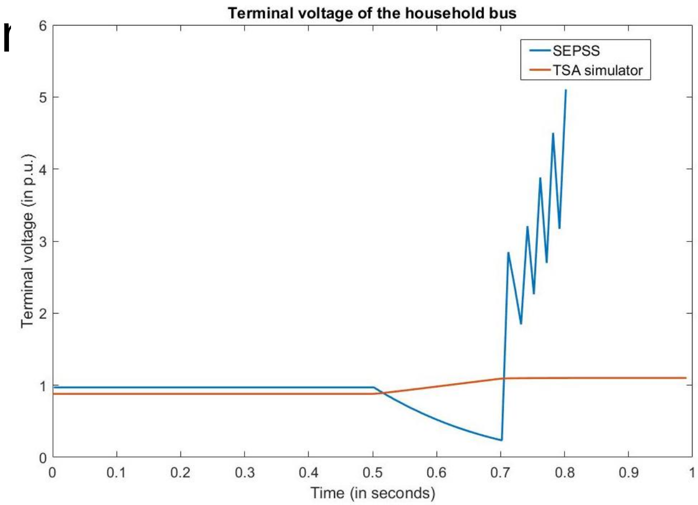
Preliminary Results: Secondary control that guarantees frequency regulation



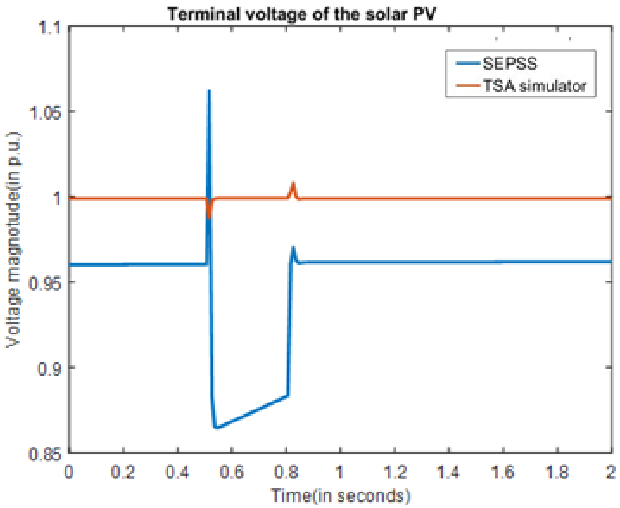


Need to model, simulate and control new phenomena

Constant PID controllers simulated using TSA software and ir



Energy based controllers simulated in TSA software and in SE



Remark 1: The system response simulated using industry simulation tools appears to be stable

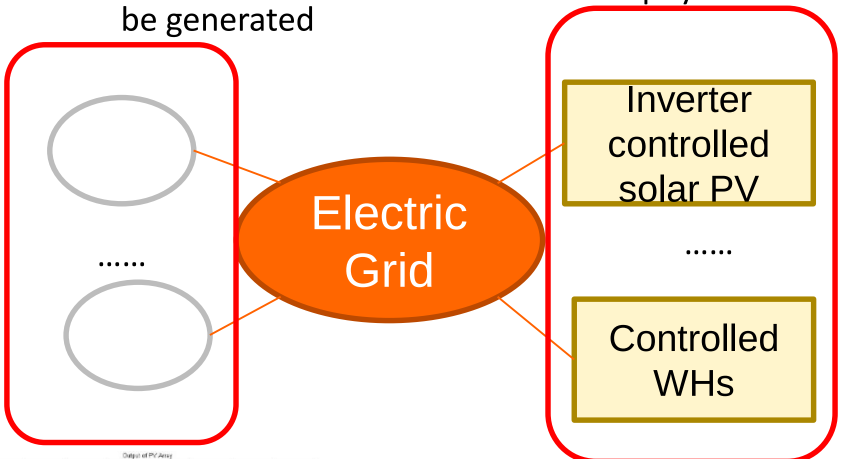
Remark 2: Industry simulation tools may not see benefits of better “smarts”

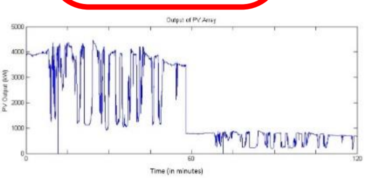
**Ilić, Marija D., Rupamathi Jaddivada, and Xia Miao. "Scalable electric power system simulator." 2018 IEEE PES Innovative Smart Grid Technologies Conference Europe (ISGT-Europe). IEEE, 2018.*

Unifying energy-based dynamical modeling

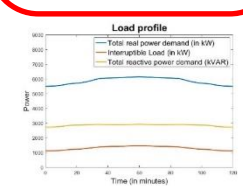
Inertia used as a proxy to rates at which energy can be generated

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) approximated system analysis valid

Basis for energy as a state variable

Power conservation laws always hold at the interfaces of components a

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 take place – ought to be captu

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.

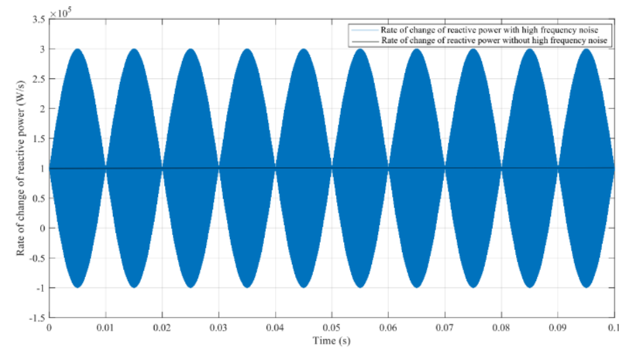
Making the case for using ``better” definition*

$$
\begin{aligned}
v(t) &= V_m\cos(\omega t) + V_n\cos(n\omega t) && (1)\\
v(t) &= L\frac{di}{dt} && (2)\\
i(t) &= \frac{V_m}{L}\int_0^t \cos(\omega t)\,dt + \frac{V_n}{L}\int_0^t \cos(n\omega t)\,dt && (3)\\
i(t) &= \frac{V_m}{\omega L}\sin(\omega t) + \frac{V_n}{n\omega L}\sin(n\omega t) && (4)\\
\dot{Q}(t) &= v\frac{di}{dt} - i\frac{dv}{dt} && (5)\\
\dot{Q}(t) &= \frac{1}{L}((V_m\cos(\omega t) + V_n\cos(n\omega t)) \times (V_m\cos(\omega t) + V_n\cos(n\omega t))\\
&+ (V_m\sin(\omega t) + V_n \times n\sin(n\omega t)) \times (V_m\sin(\omega t) + \frac{V_n}{n}\sin(n\omega t))) && (6)
\end{aligned}
$$

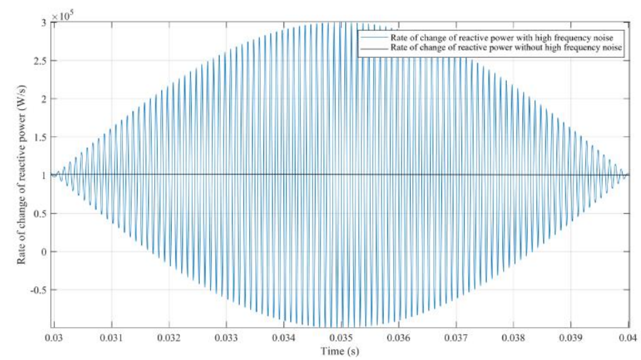
New definition of rate of change of reactive power—beyond Time Varying Phasor (TVP) Modeling

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.

**Zoomed out view- The effect of switching noise on rate of change of reactive power; 10kHz noise superposed on 50 Hz sinusoidal signal with 1% amplitude of fundamental component (100V) for a simple inductive energy storage of 100mH.



**Zoomed in view— as high as 200% swing in the rate of change of reactive power varying at the rate of switching frequency as compared to a fixed reactive power rate value when there is no high frequency noise.



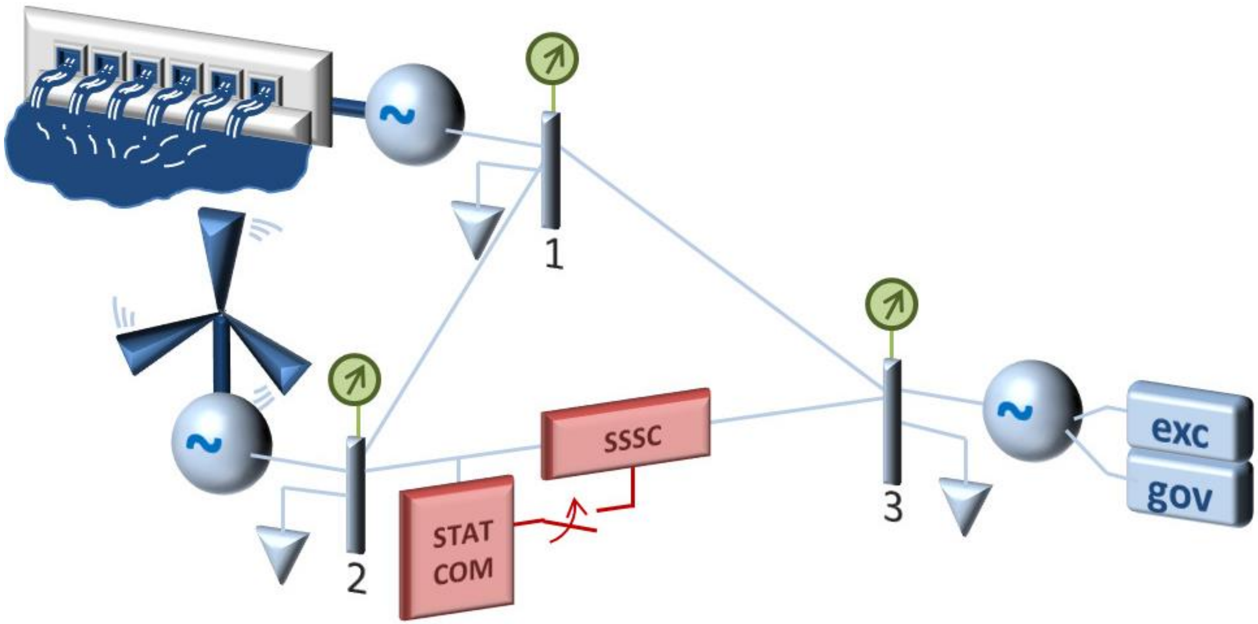
***Simulations by Dr. Pallavi Bardawhaj, MIT postodoc, June 2021*

Generalized intVar dz/dt= [p(t) dQ/dt]

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.

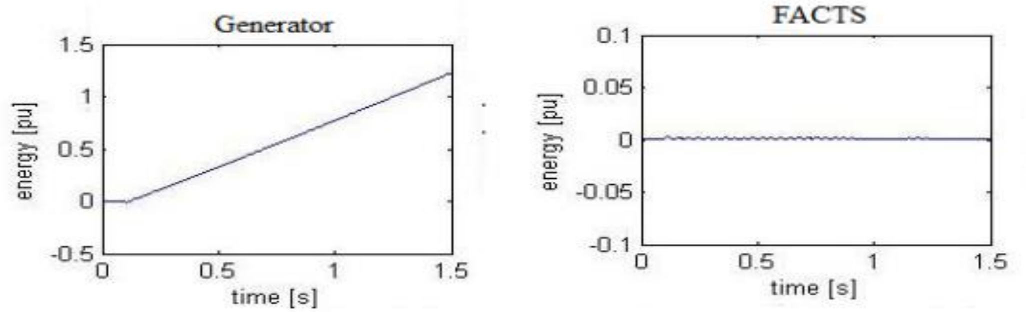
Jaddivada, Rupamathi, A unified modeling for control of generalized reactive power dynamics in electric energy systems, MIT EECS PhD thesis, July 2020.

Controlling BPS with IBRs



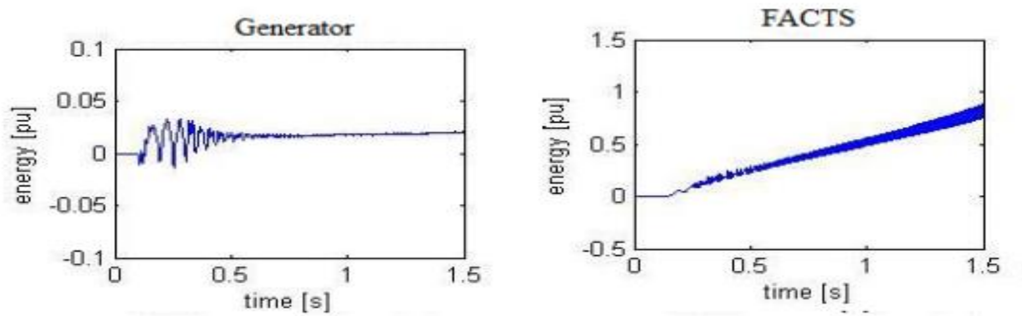
Cvetković, M., & Ilić, M. D. (2014). Ectropy-based nonlinear control of facts for transient stabilization.
IEEE Transactions on Power Systems, *29*(6), 3012-3020.

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

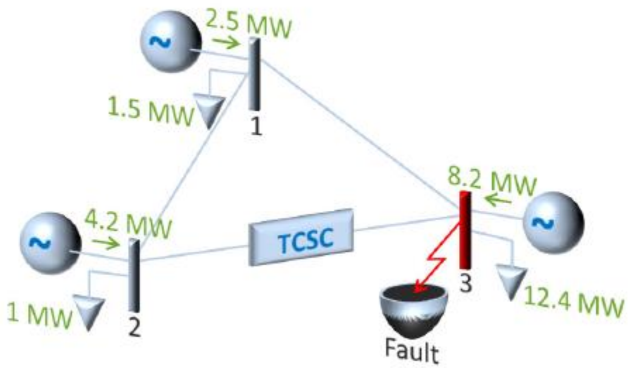


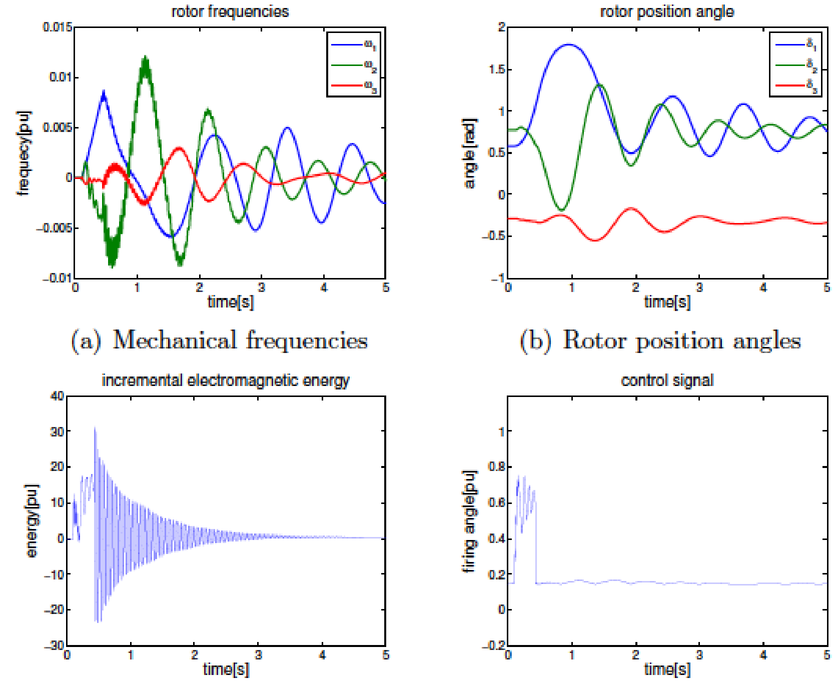
(c) Generator energy increment in a controlled system

(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

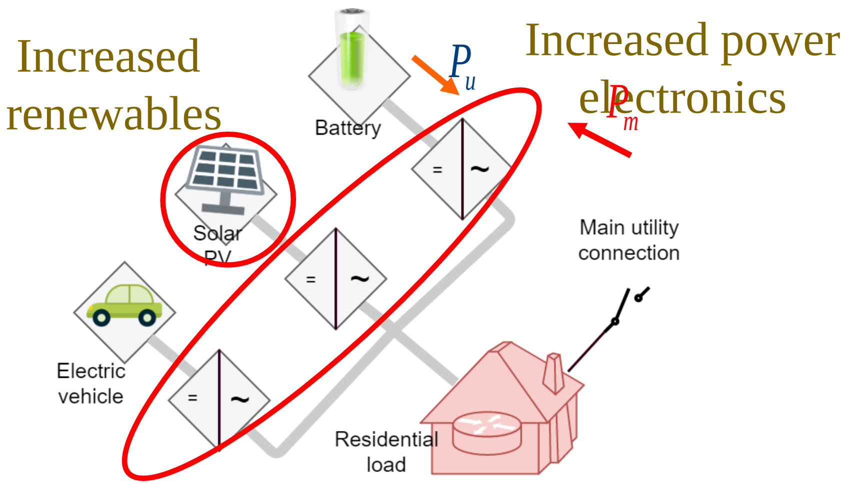
(b) Rotor position angles

(c) Increment in accumulated energy

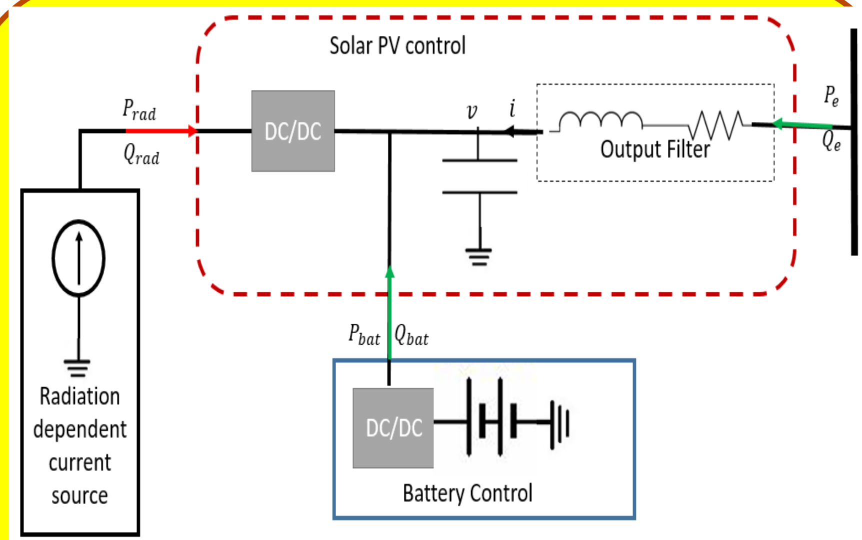
(d) Controller signal

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!!!

Example of a physics-based solar PV droop

Energy Space Model:

$$\dot{E}(t) = P_{rad}(t) + P_{bat}(t) + P_e(t) - \frac{E(t)}{\tau} = p(t)$$

$$\dot{p}(t) = 4E_t(t) - \dot{Q}_{rad}(t) - \dot{Q}_{bat}(t) - \dot{Q}_e(t)$$

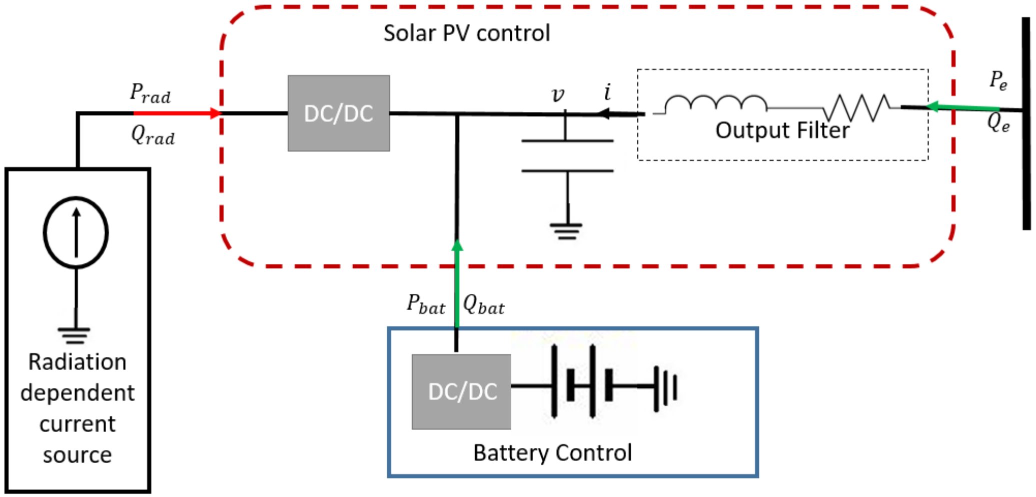
Here, $E(t) = \frac{1}{2}Li(t)^2 + \frac{1}{2}Cv(t)^2$

- 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: $\Delta P[k] = \sigma\Delta W[k]$

Proof of concept energy control – power load

- IBR SERVING CONSTANT POWER

(VOLTAGE COLLAPSE CASE)

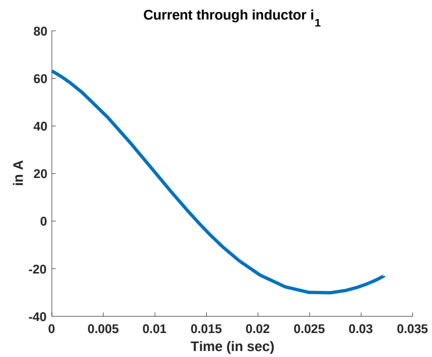
- IBR with two loops
- IBR with PID control
- ENERGY CONTROL
- Aligning power part of intVar
- Aligning both power and rate of change of reactive power

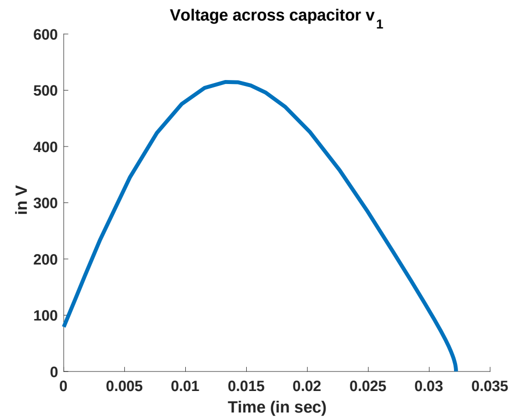
- IBR SERVING INTERMITTENT POWER(OSCILLATORY CASE)

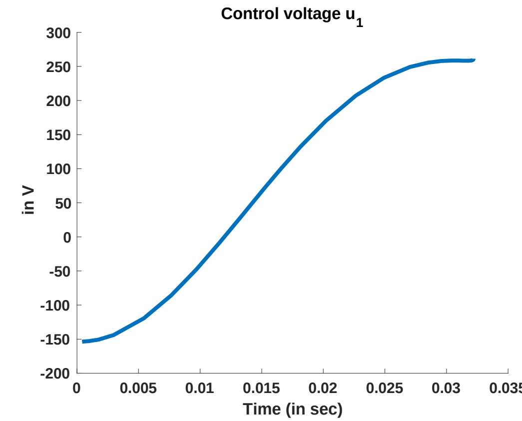
- IBR with two loops
- IBR with PID control
- ENERGY CONTROL
- Aligning power part of intVar
- Aligning both power and rate of change of reactive power

UNDERSTANDING EFFECTS OF VARIOUS CONTROL ON ENERGY DYNAMICS

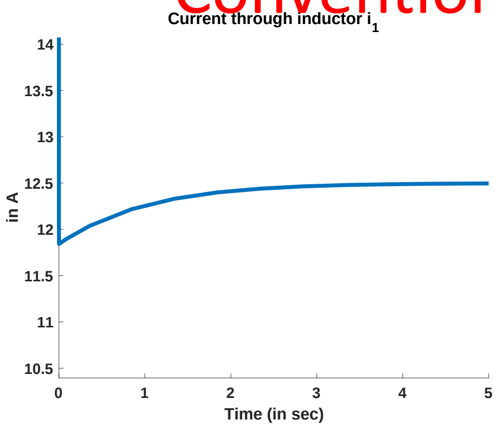
Conventional full state feedback (two loop IBR)

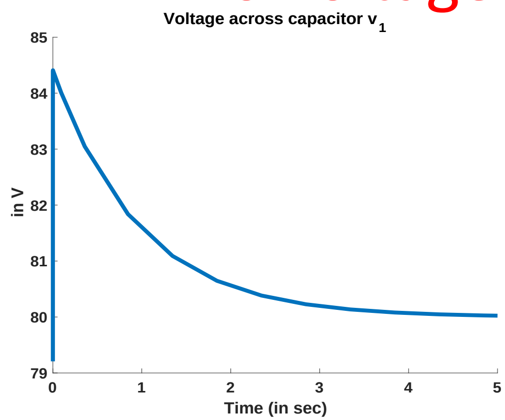


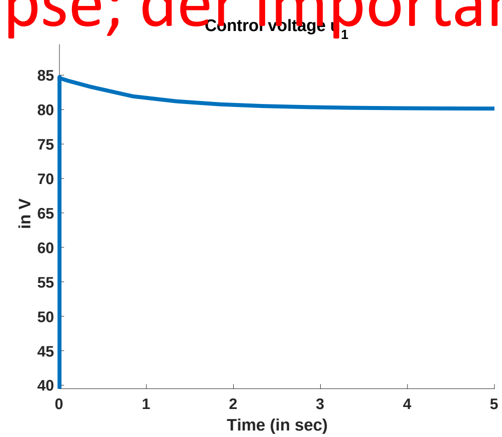




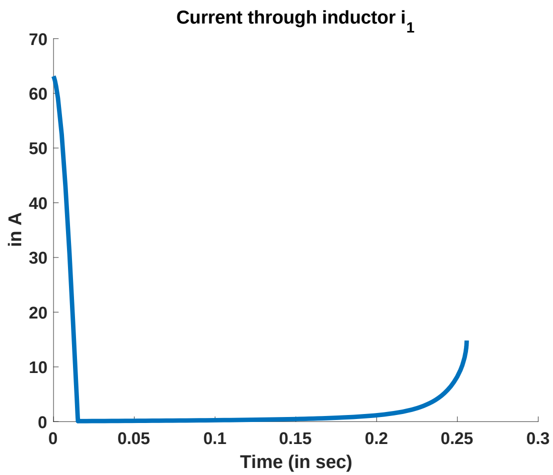
Conventional PID –no voltage collapse; der important

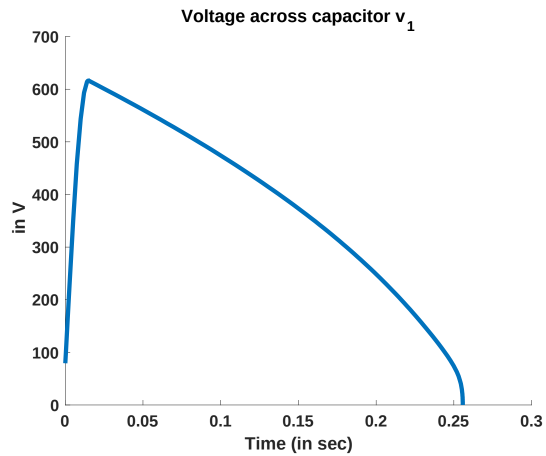


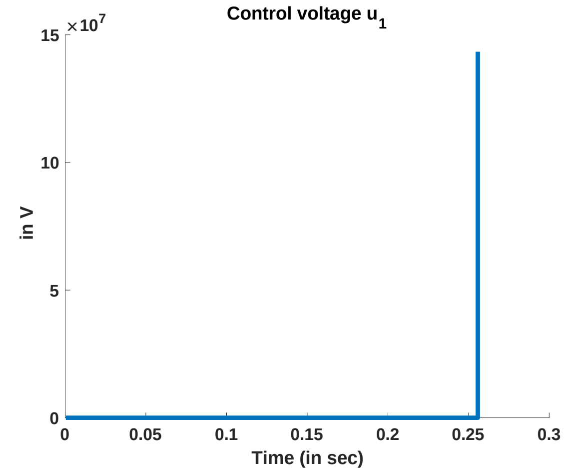


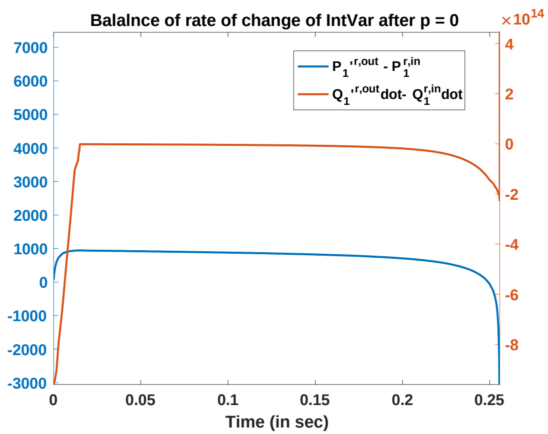


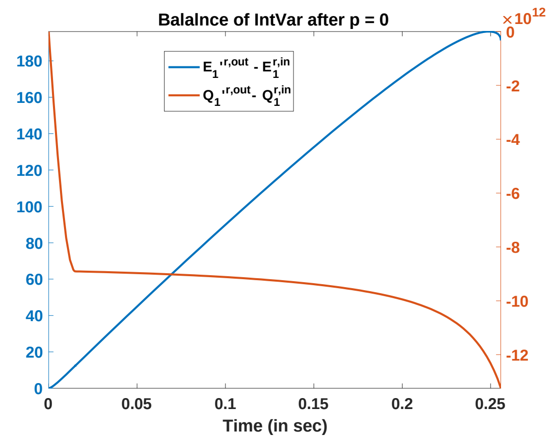
Single time scale energy control aligning P only





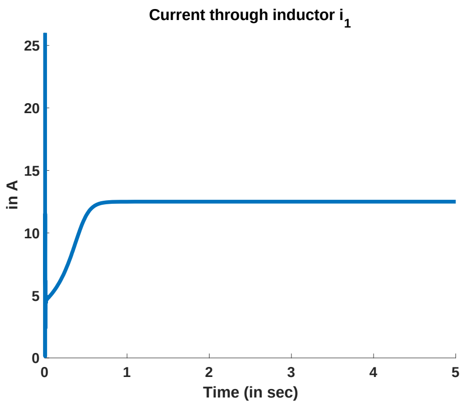


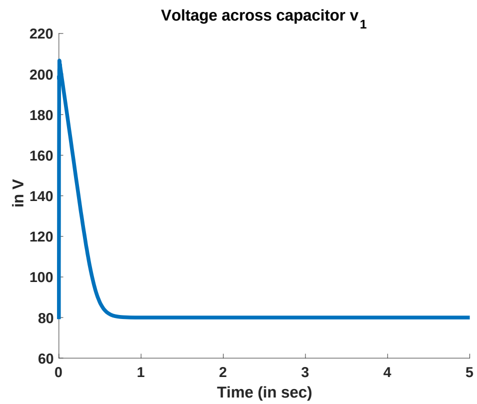


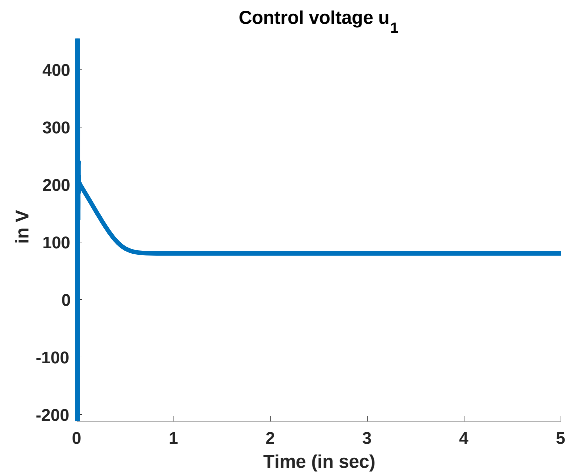


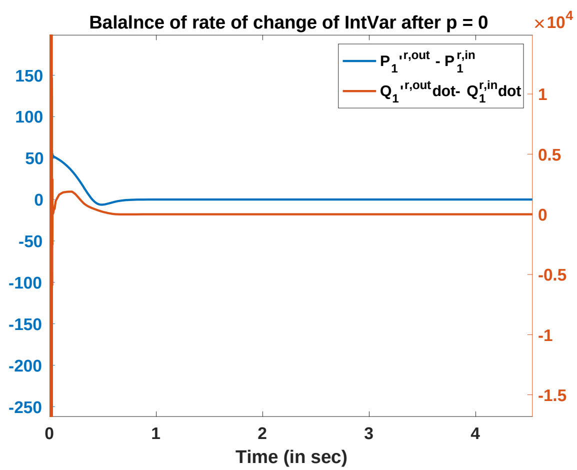
ENERGY DYNAMICS

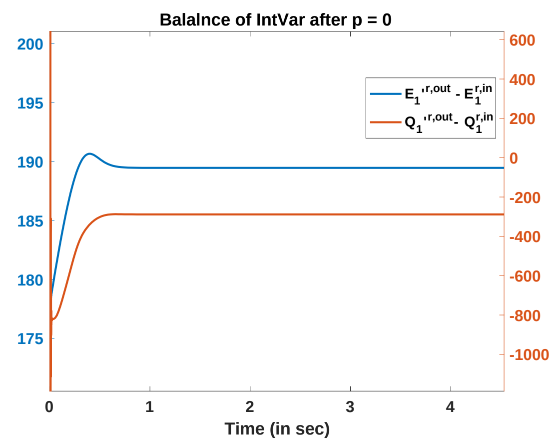
Two time scale energy control—aligning P and Qdot



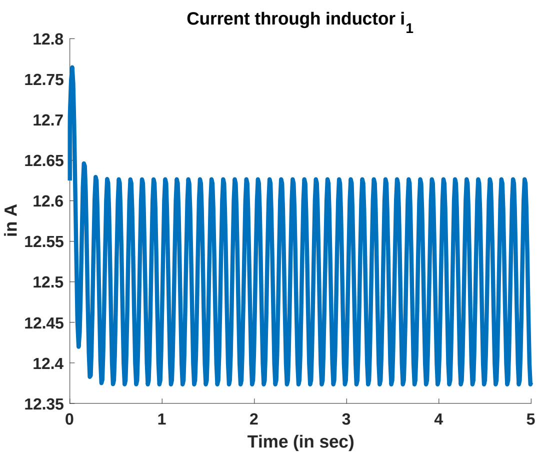


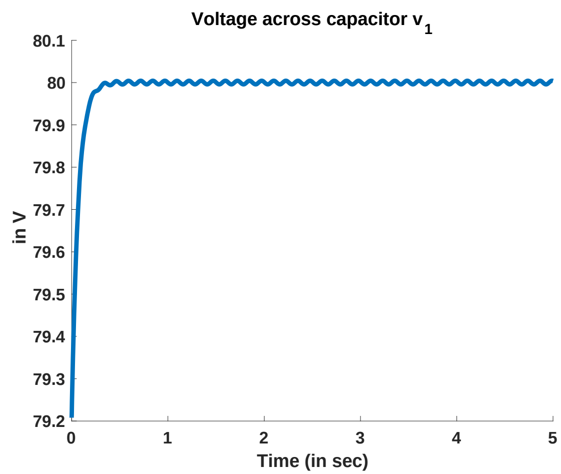


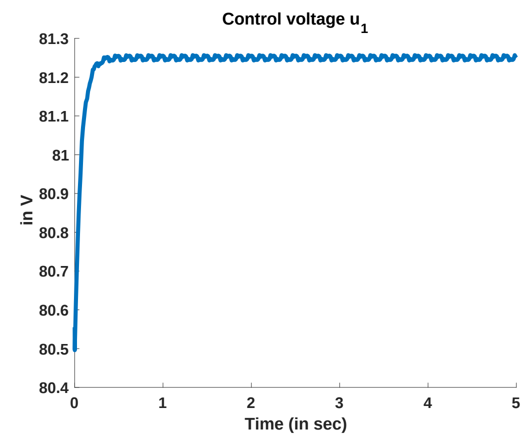


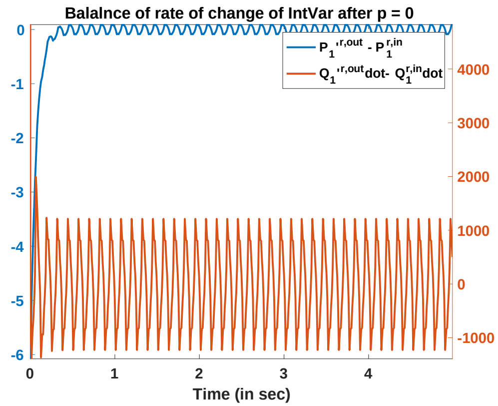


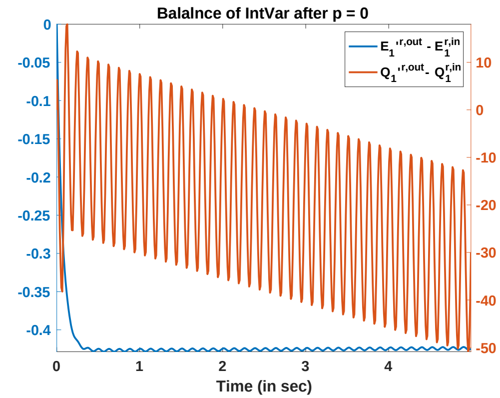
IBR for INTERMITTENT POWER (OSCILLATORY CASE)
Conventional full state feedback



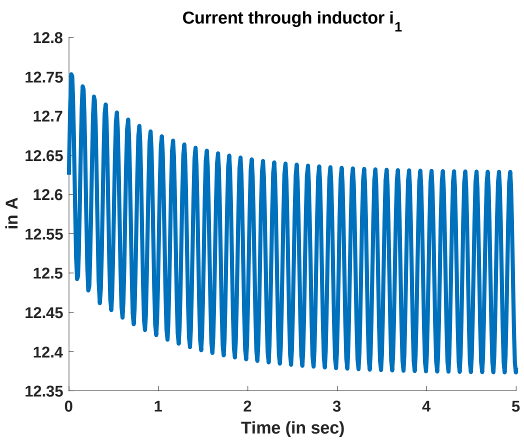


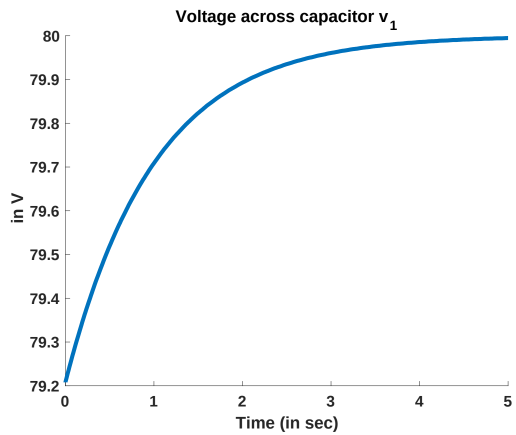


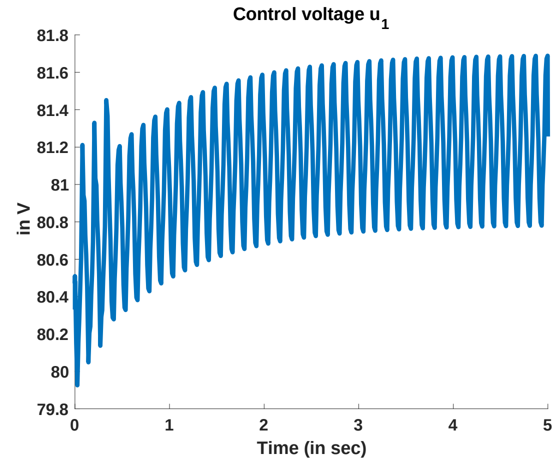


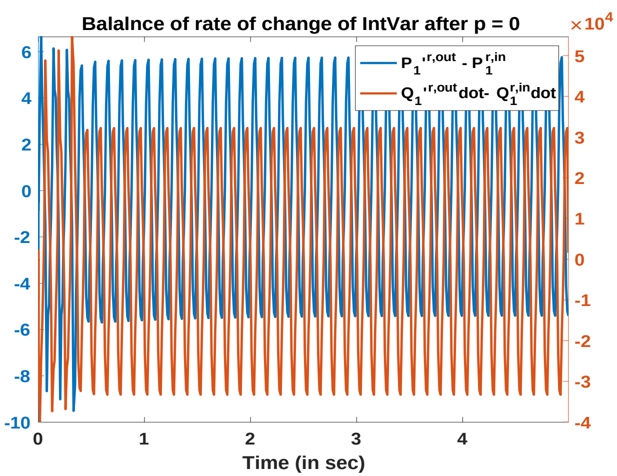


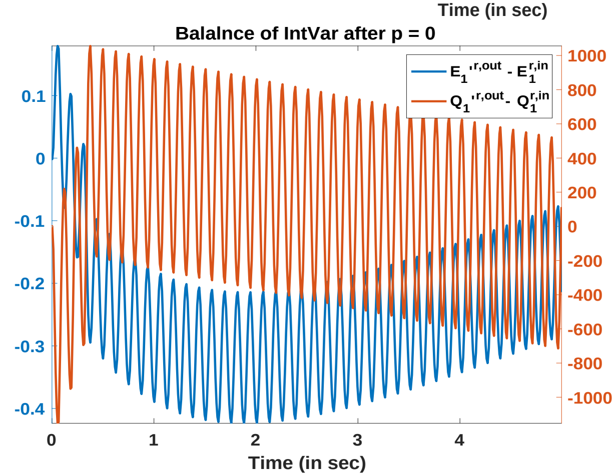
Conventional PD control responding to Vi



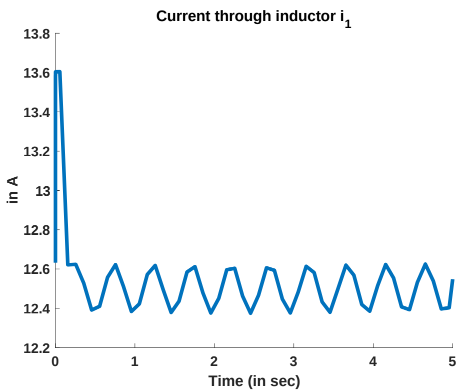


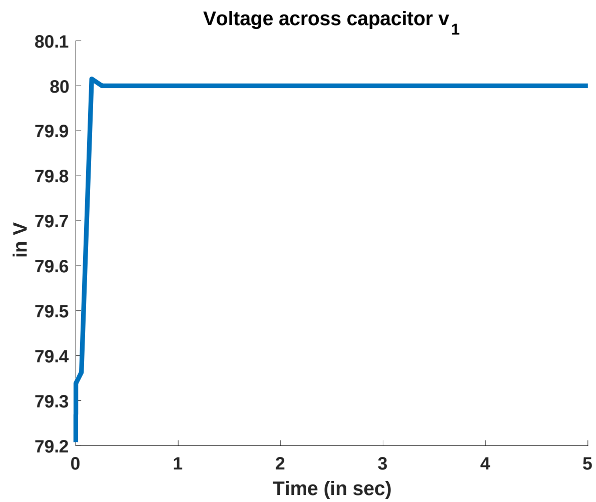


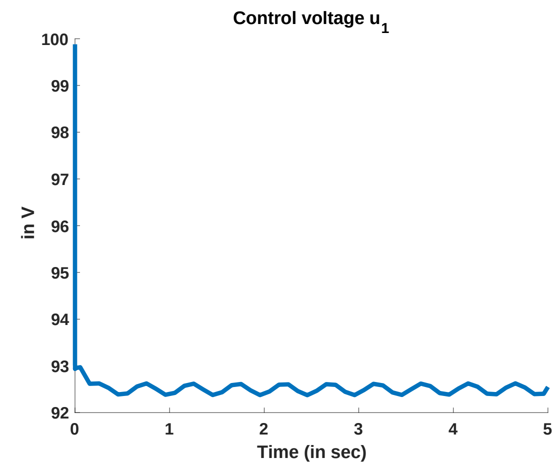


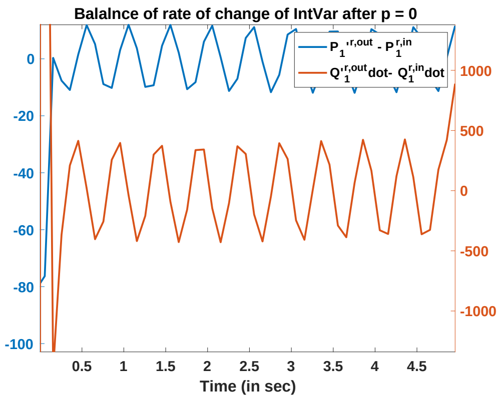


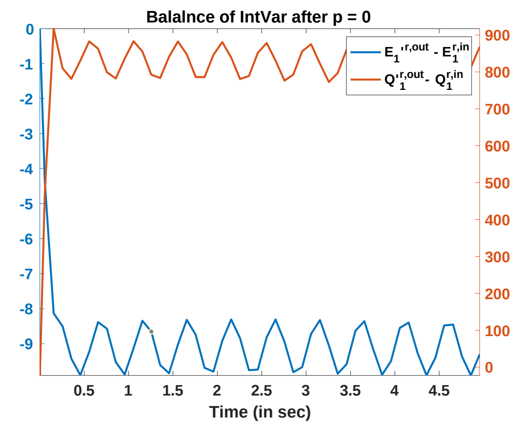
Single time scale energy control responding to Prout – with SMC



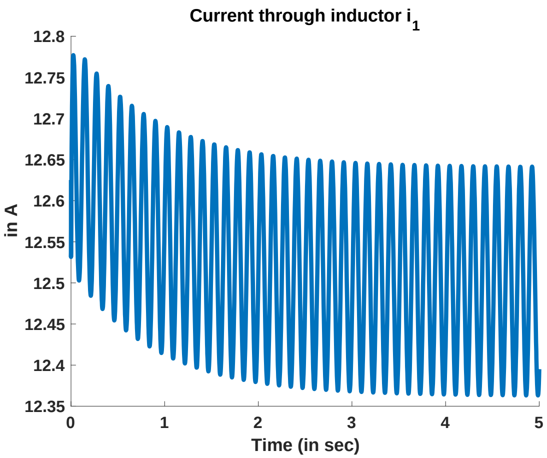


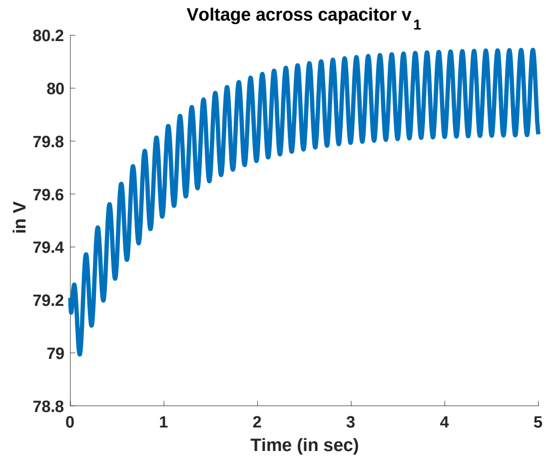


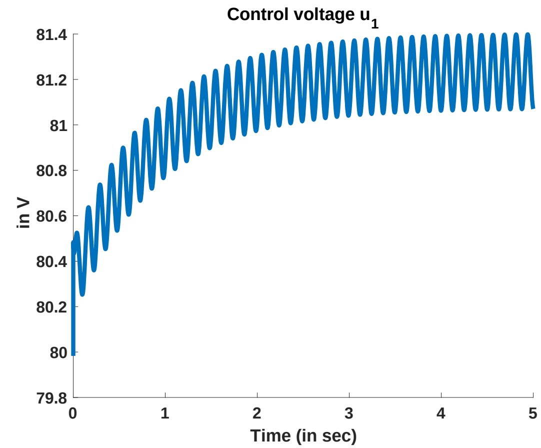


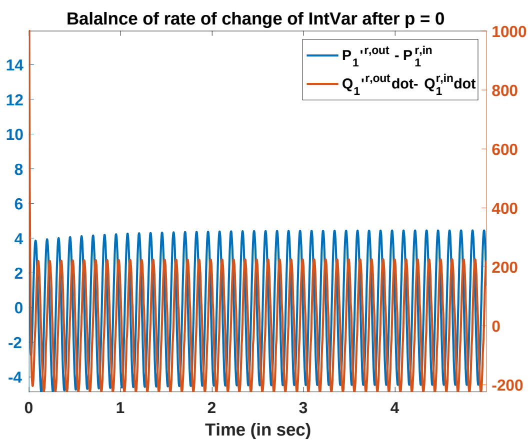


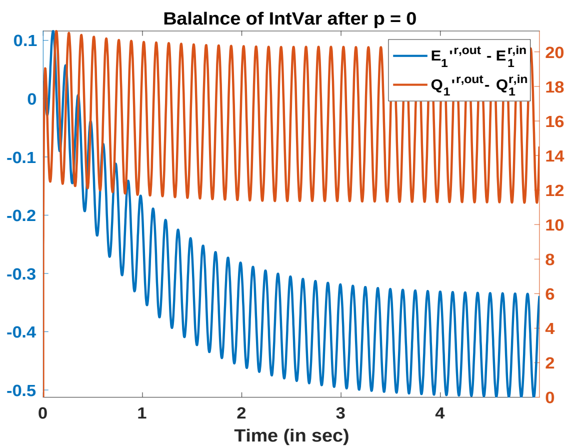
Two time scale energy control ks = 1, kf = 1



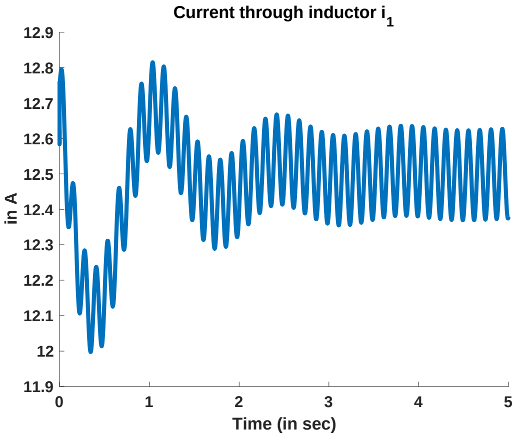


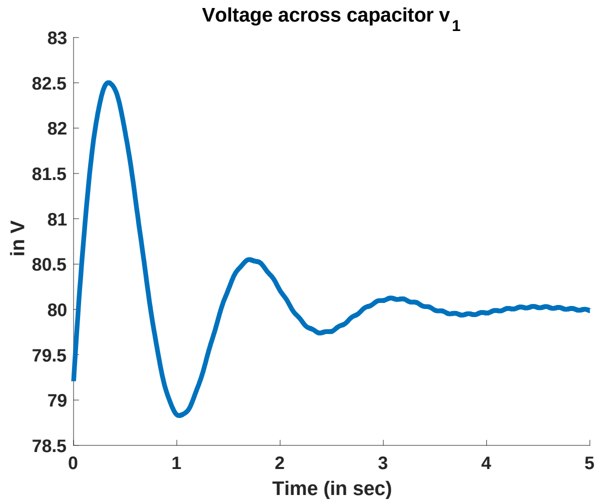


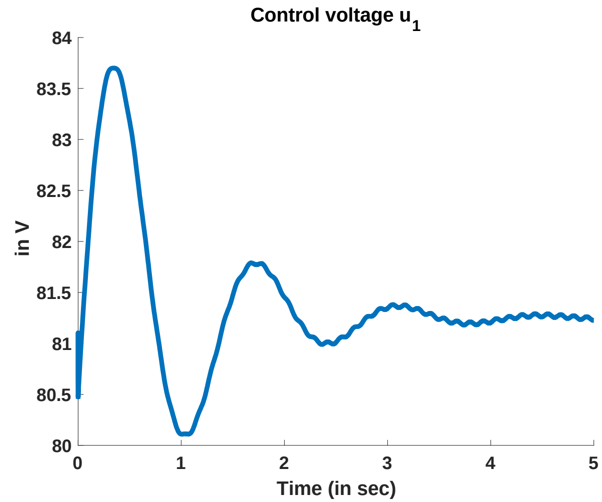


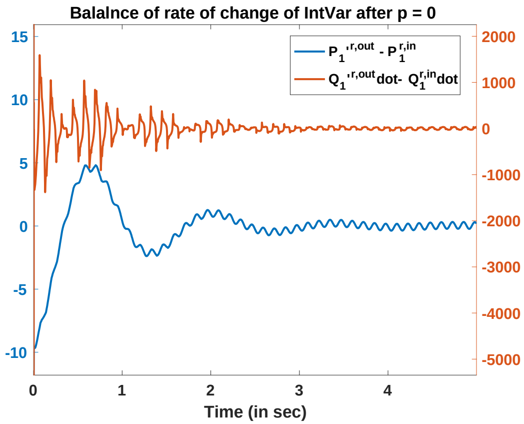


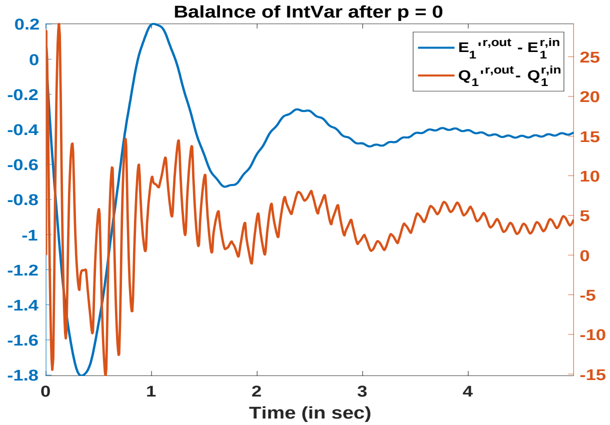
Two time scale energy control
ks = 1e2, kf = 1e4



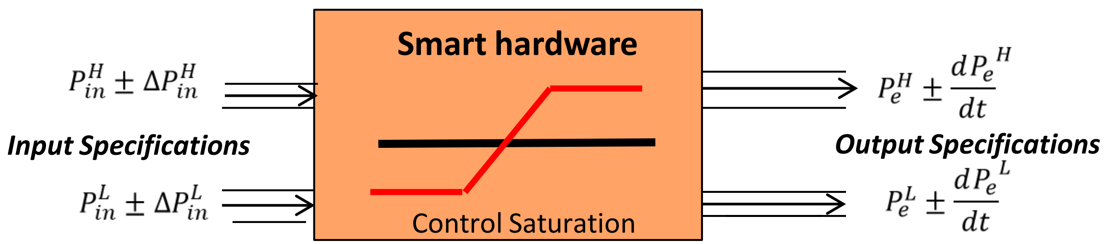








Unified component specifications and interaction conditions in energy space for stable/feasible operations



Sufficient conditions feasible and stable system in energy space:

- Components in closed loop dissipative
- Cumulative power over time into the component larger than cumulative power out of the component

Distributed near optimal control—open R&D (still need for minimal coordination)

Possible way forward: Multi-layered functional specifications

- Interactive model of interconnected systems

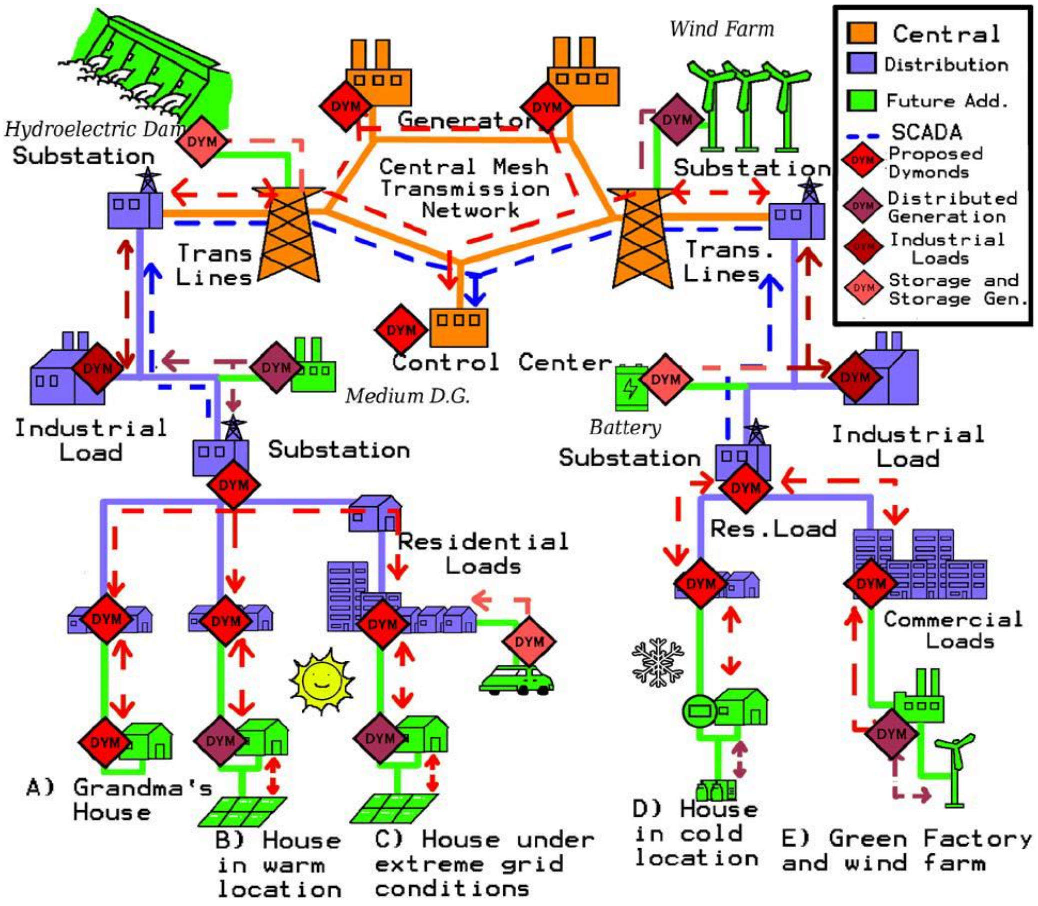
--multi-layered complexity

--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

DyMonDS framework



-protocols for minimal information exchange reliably and efficiently

-distributed decisions and intVar-specifications as the basis for choice

-technology agnostic for candidate architectures

Ilić, Marija D. "Dynamic monitoring and decision systems for enabling sustainable energy services." Proceedings of the IEEE 99.1 (2010): 58-79.

Conclusions: Three steps forward

- **Principle 1: 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.
- **Principle 2: Next generation SCADA to support this information exchange among iBAs.** As the operating conditions vary, stakeholders process the shared information, as sketched in Fig- ures 1 and 3; optimize their own sub-objectives, subject to own constraints and preferences; and, communicate back their willingness to participate in system-wide integration.
- **Principle 3: The basic information exchange is in terms of energy, power and rate of change of reactive power intVars with physical interpretation as a generalized ACE.**

Thank you.
Questions?

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