First principles, modeling, design and control for microgrids

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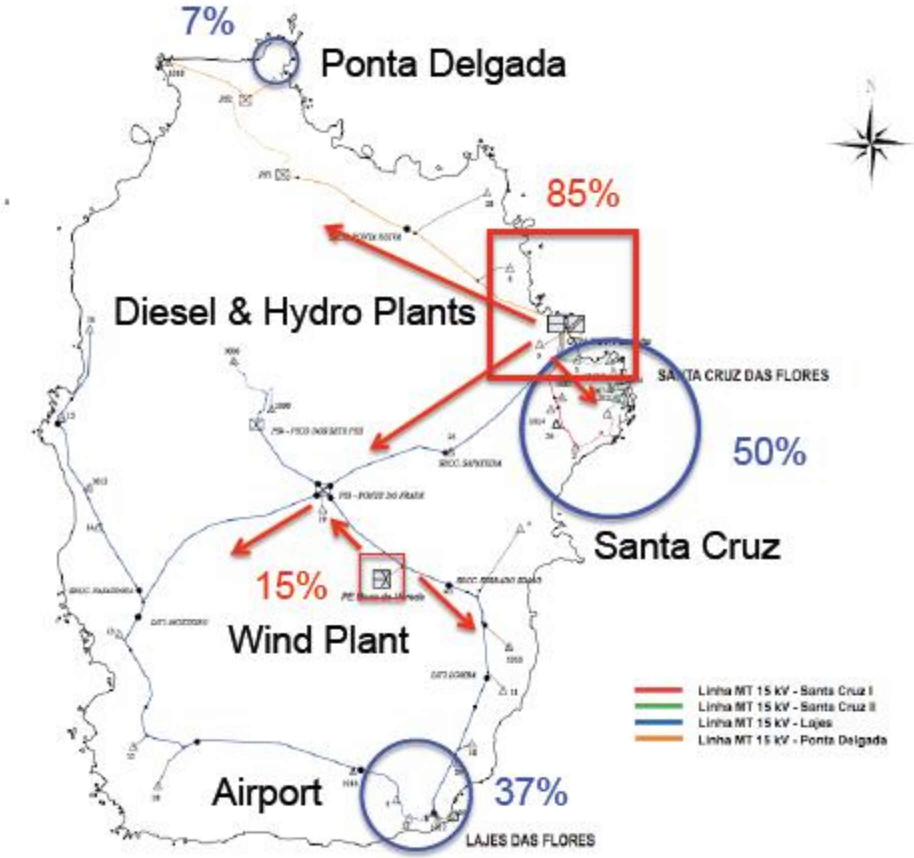
Presentation at the ARPA-E Workshop

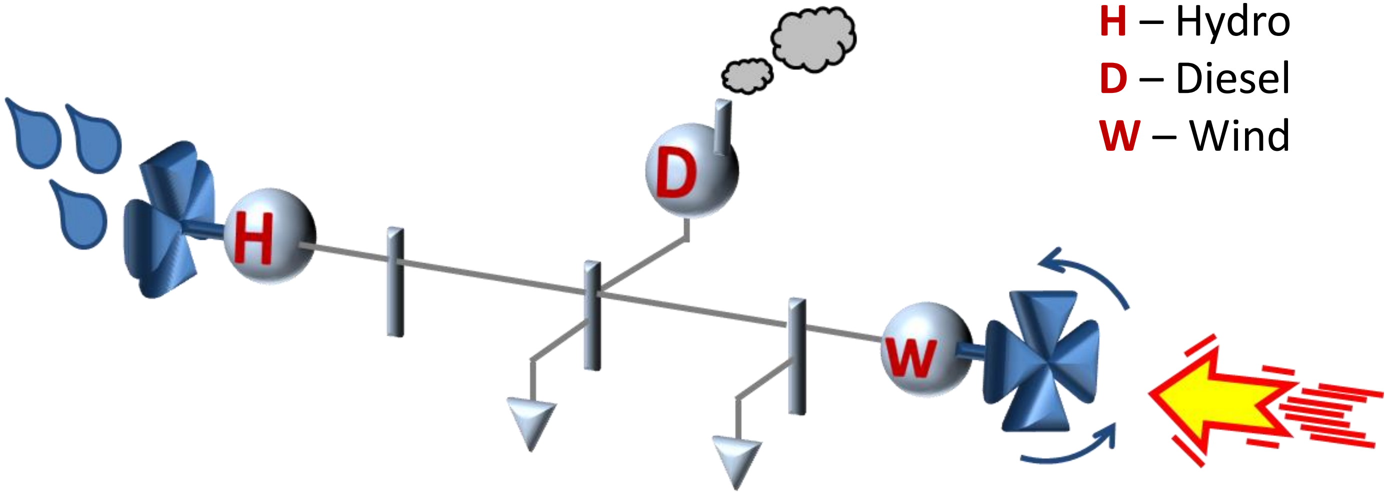
October5,2020

Outline

- Microgrids studied (Azores Islands, Puerto Rico; distribution feeders (Sheriff, Banshee; large continental IEEE 8500 bus grid)
  - Scaled up in size; diverse resources (wind, PVs, CHPs, storage), loads (priority, controlled, uncontrolled), grid topologies (stand-alone; recongifurable with T&D)
- Lessons learned, Challenge problems
  - Systems thinking key; need for transparent control co-design essential for meeting any metrics desired; numerical evidence w/r to metrics dependence on control
- Rethinking the first principles: Unified modeling, design, control
  - Modular, interactive modeling of components –I/O characterization
  - Unified multi-layering of interactions for robustness and efficiency
- Three technology-agnostic principles to make it work
- New high tech business opportunities to innovate at value; collaborations

Flores Island Power System-Typical micro-grid of the future*





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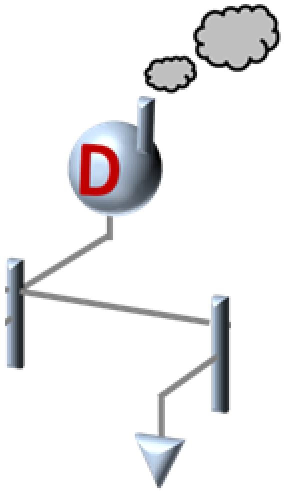
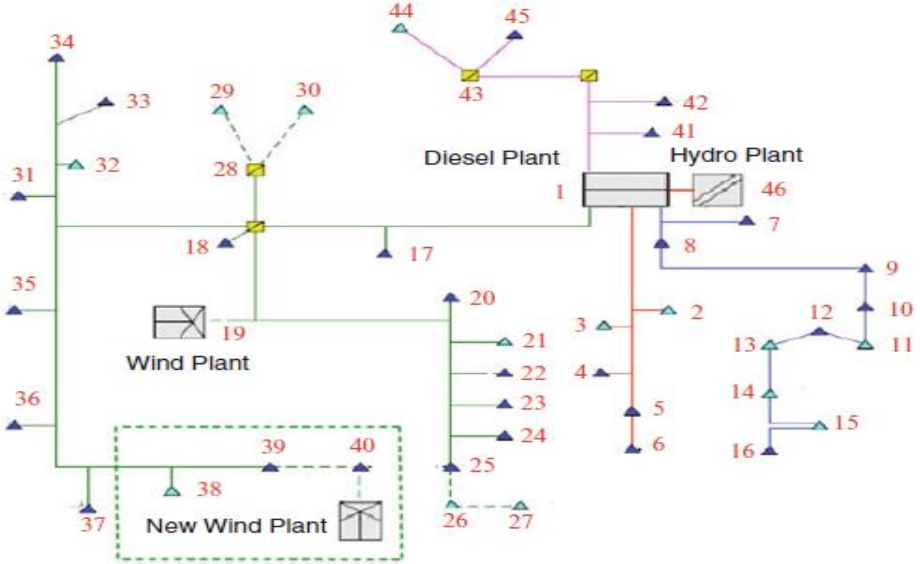


To?



*Publicly available data, modeling and control in 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.

Effects of microgrid controller (AC OPF-based)

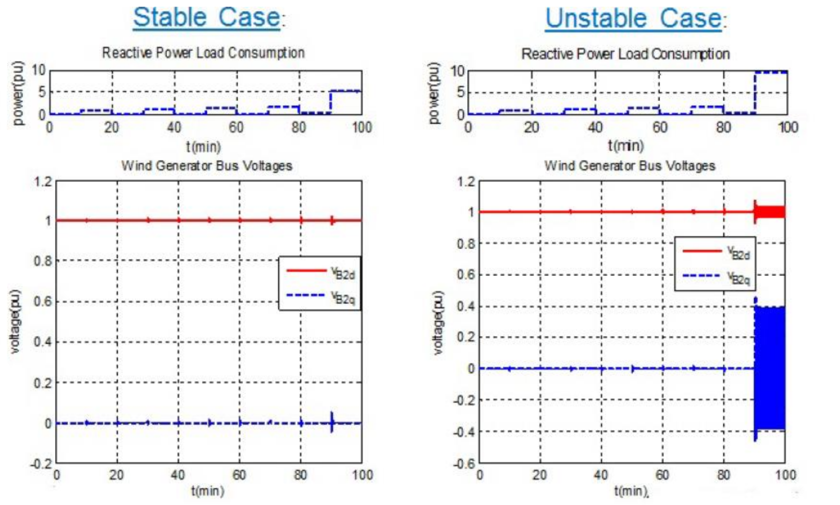
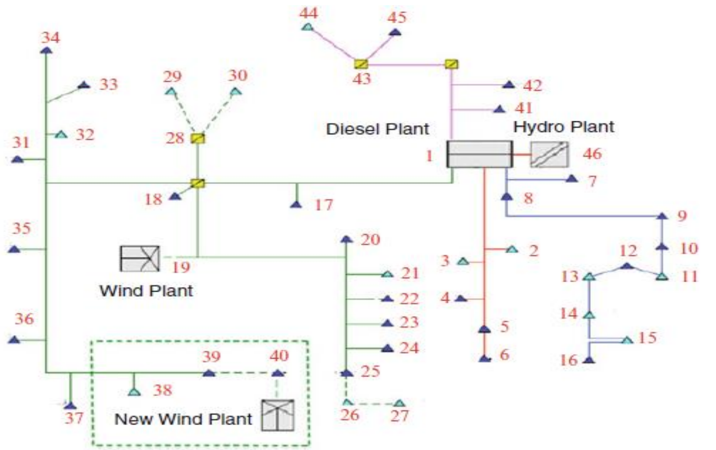


Fig. 33. Simulation results demonstrating that the reactive power set points are crucially important to the dynamic stability of the system



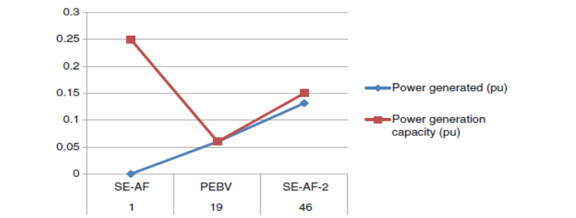


Fig. 13.3 Geographical distribution of optimal generation in Flores, wind power O&M cost 88 $/MWh

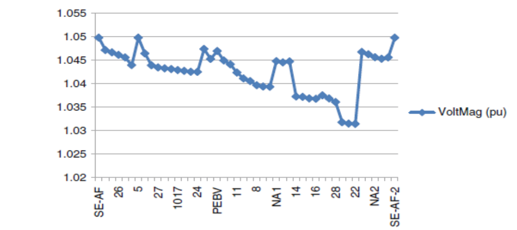


Fig. 13.4 Geographical distribution of optimized voltages in Flores, wind power O&M cost 88 $/MWh

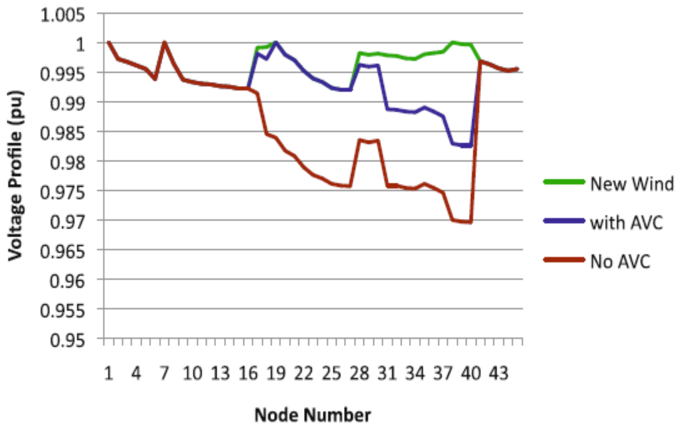


Fig. 12.6 Voltage profile of the island in three different scenarios

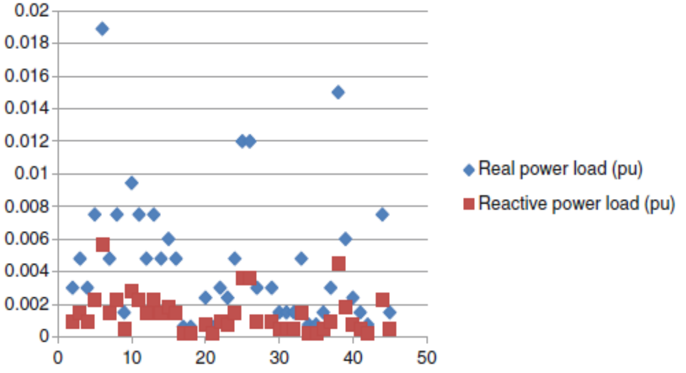


Fig. 13.2 Geographical distribution of load in Flores; the *x*-axis is the bus number 1–46; the *y*-axis is load in per unit (pu)

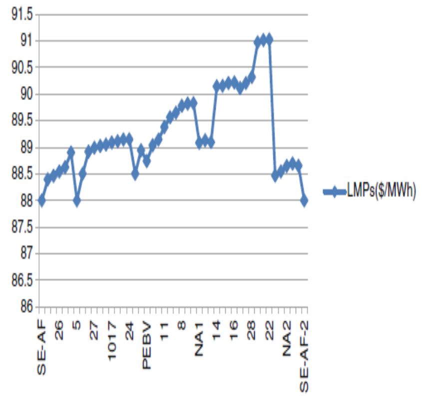


Fig. 13.5 Geographical distribution of LMPs in Flores; wind power O&M cost 88 $/MWh

Potential to add PVs and support them with EVs

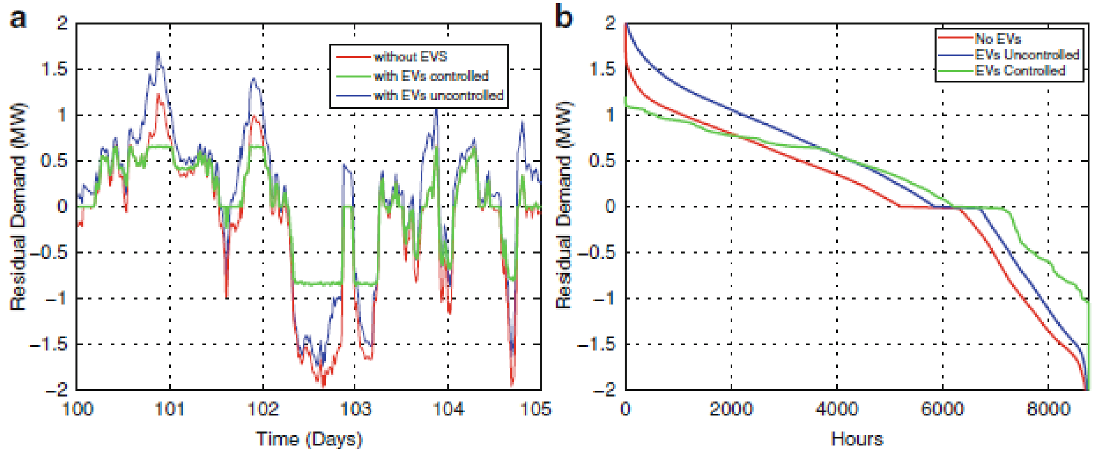


Fig. 11.9 Residual demand in three scenarios for the moderate wind and solar scenario and 1,000 EVs in a 5-day spring period (a) and the load duration curves (b)

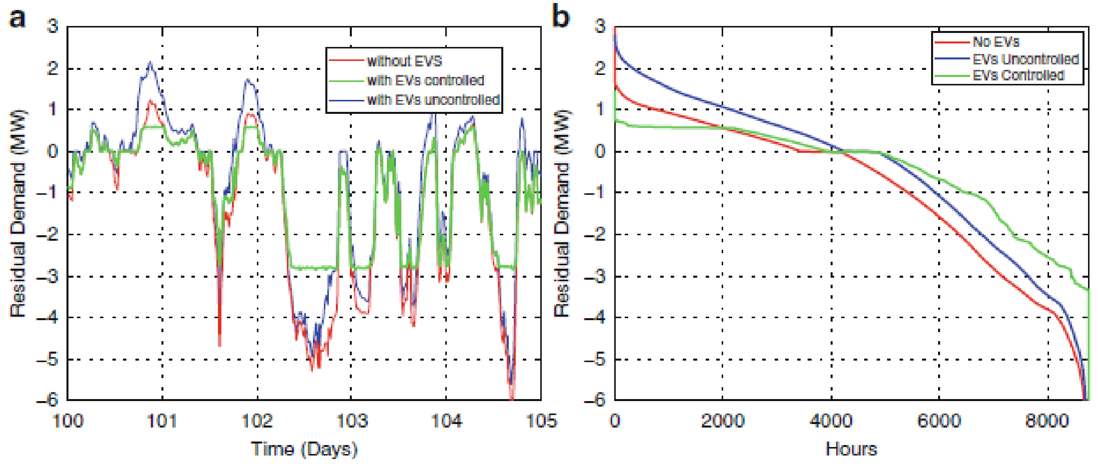


Fig. 11.11 Residual demand for the maximum wind and solar scenario and 2,000 EVs in a 5-day spring period (a) and the load duration curves (b)

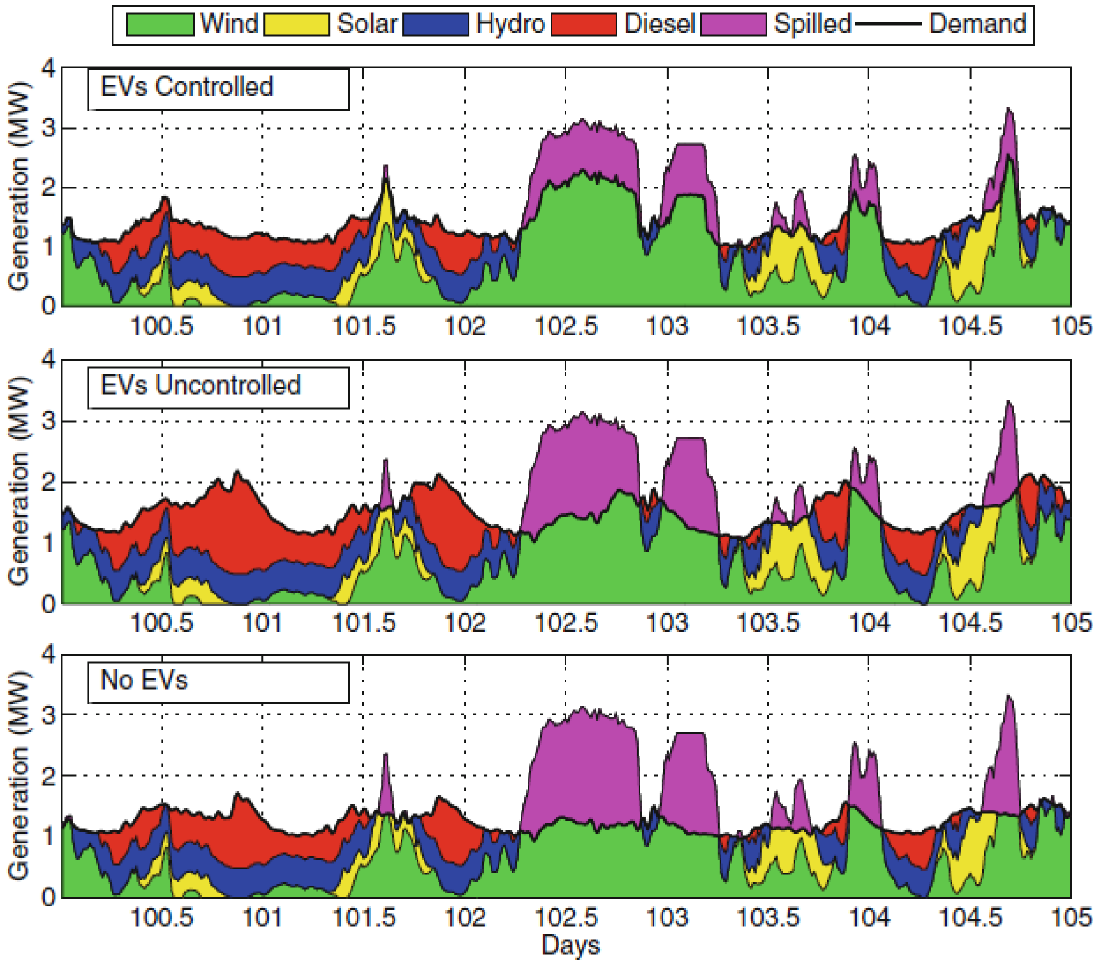


Fig. 11.10 Use of different generation types for a period in spring with 1,000 EVs in different scenarios for the case with moderate wind and solar

Major concern: Frequency regulation?

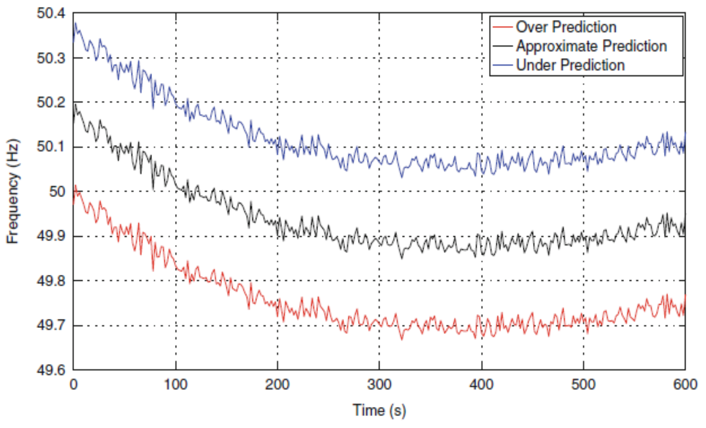
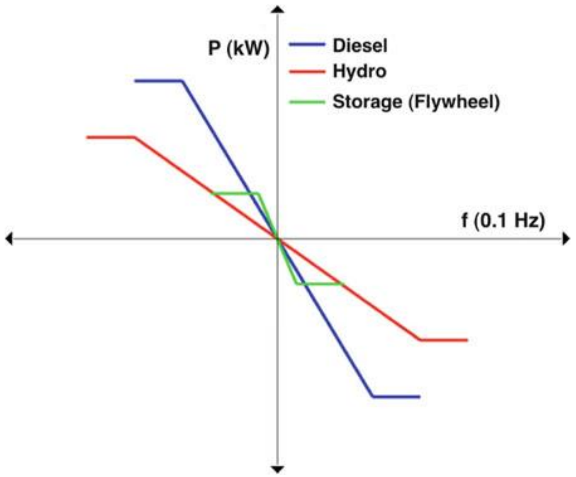


Fig. 14.3 Flores: persistent frequency deviations in the system



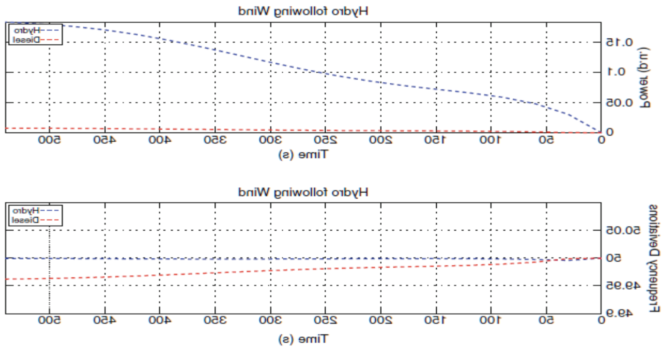


Fig. 14.9 Hydro unit balancing intra-dispatch wind variations

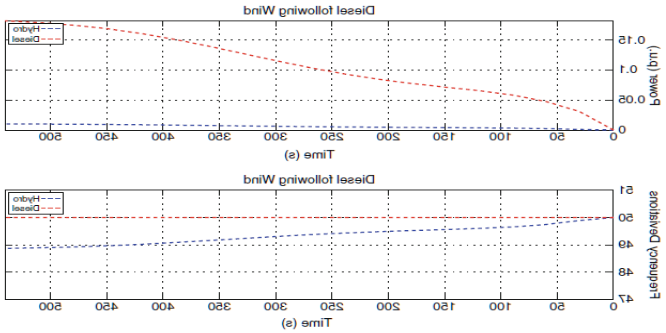


Fig. 14.10 Diesel unit balancing intra-dispatch wind variations

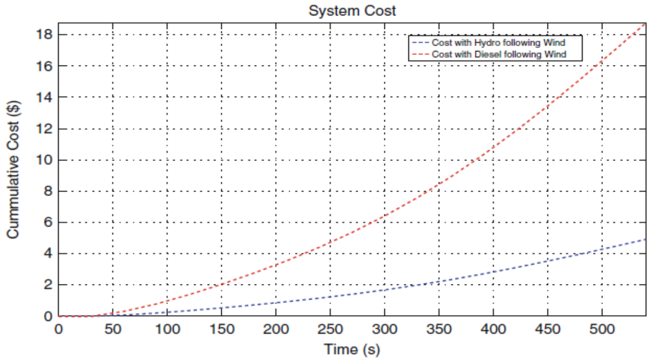
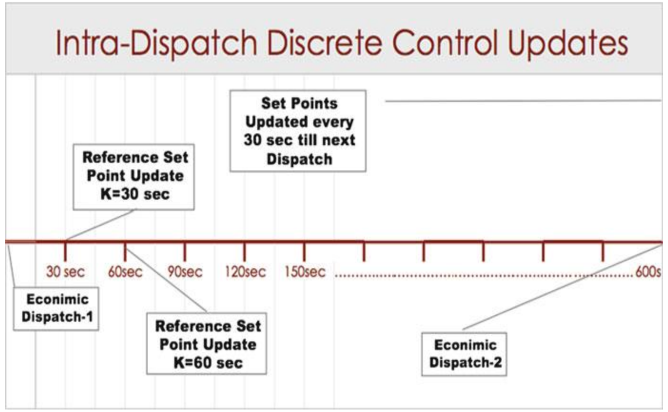


Fig. 14.14 Comparing cumulative cost over 10 min



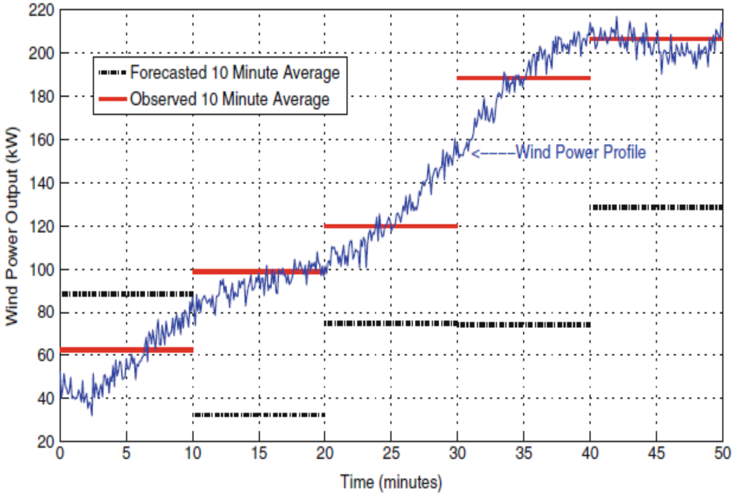


Fig. 14.1 10-Min ahead wind power forecast and actual wind power output

How to make it robust/small-signal stable?

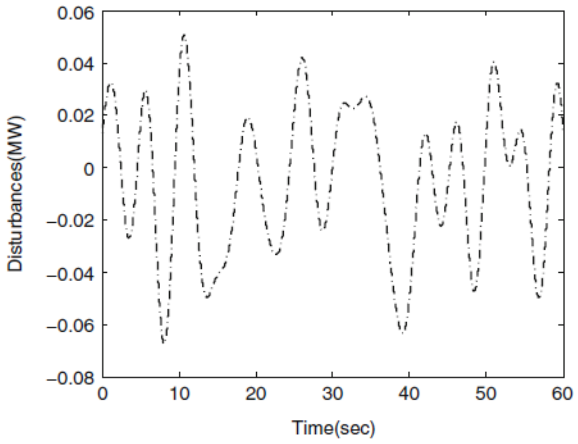


Fig. 15.7 Wind power disturbances under current penetration level

Table 15.1 Eigenvalues of the dynamic components

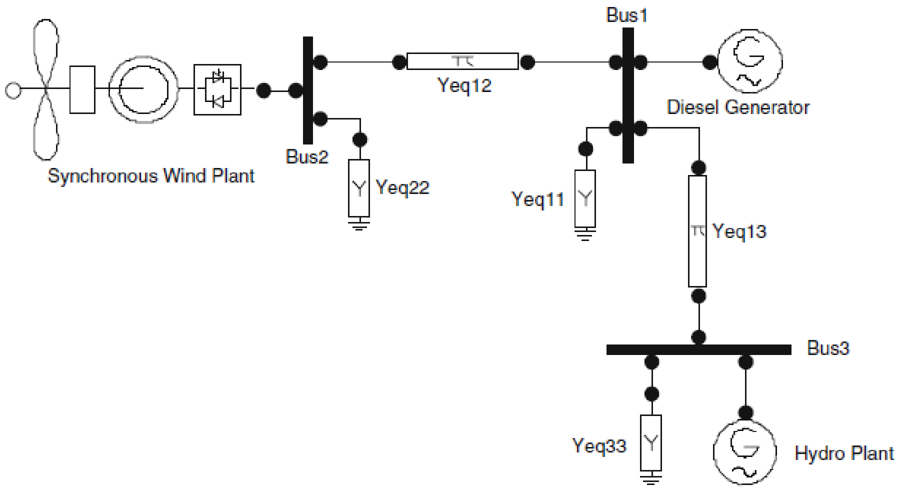
Generator components	Eigenvalues of the components
Diesel	$-0.03, -0.8238 \pm 9.867i$
Hydro	$0, -126.71, -1.3742, -0.0330, -0.4606$
Wind	$0, -0.0215$

Table 15.2 Eigenvalues of the dynamic components with a flywheel as local control

Generator components	Eigenvalues of the components
Diesel	$-0.03, -0.8349 \pm 9.867i$
Hydro	$0, -126.7109, -1.3741, -0.0447, -0.4606$
Wind	$0, -0.1288$

Table 15.3 Eigenvalues of the interconnected system

	Eigenvalues
Interconnected Flores system without local flywheel	$0.03 \pm 32.73i, -126.71, -0.65 \pm 9.83, -0.17 \pm 2.86i, -0.03, -1.39, -0.46$
Interconnected Flores system with local flywheel	$0.07 \pm 32.73i, -126.71, -0.67 \pm 9.83, -0.18 \pm 2.87i, -0.03, -1.39, -0.46$



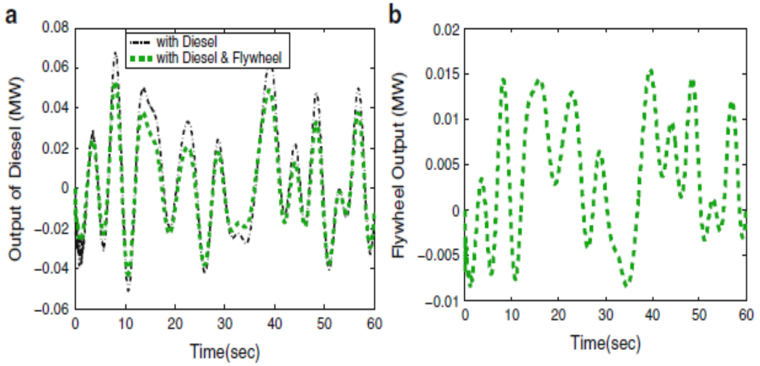


Fig. 15.9 Output of diesel and flywheel in response to frequency deviations, Case 1: system with synchronous wind generator. (a) Output of diesel generator. (b) Output of flywheel

Table 15.4 Eigenvalues of the dynamic components

Generator components	Eigenvalues of the components
Diesel	$-0.03, -0.8238 \pm 9.8670i$
Hydro	$0, -126.7109, -1.3742, -0.0330, -0.4606$

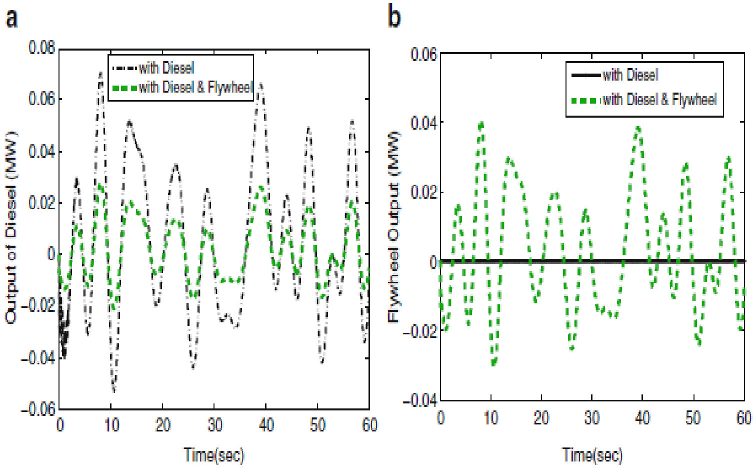
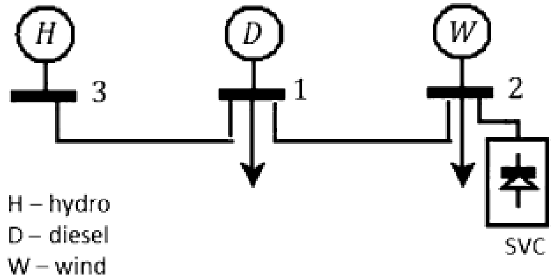


Fig. 15.11 Output of diesel and flywheel in response to frequency deviations, Case 2: system with negative load wind generator. (a) Output of diesel generator. (b) Output of flywheel

Transient stabilization in systems with wind power –SVC

Potential of Nonlinear Fast Power-Electronically-Switched Storage



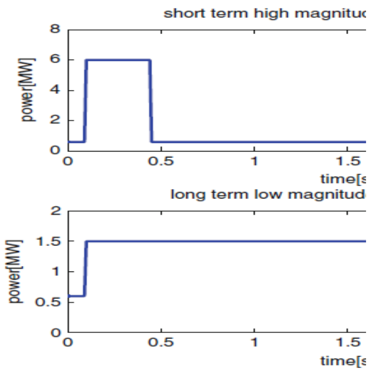


Fig. 19.2 Wind disturbances simulated in the Flores e

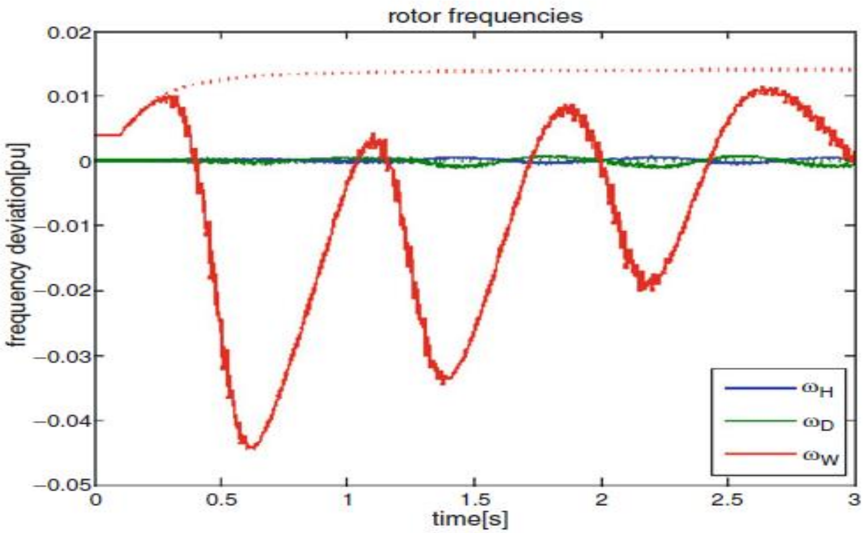


Fig. 19.16 Mechanical frequency of all generators in the system during a long-term low-magnitude wind perturbation: (a) *dashed* (without control on the SVC), (b) *solid* (with control on the SVC)

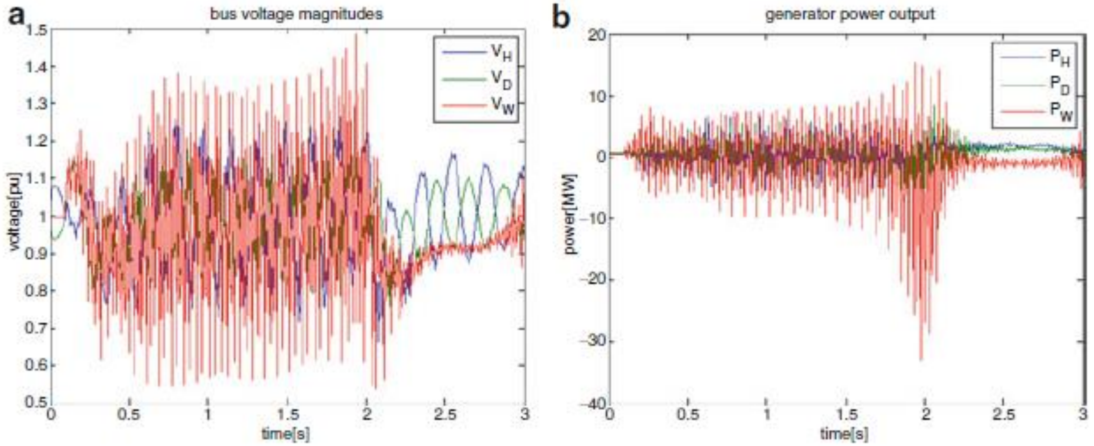


Fig. 19.14 (a) Voltage on the buses and (b) the electric power output of the generators if the system is controlled by the proposed energy-based controller

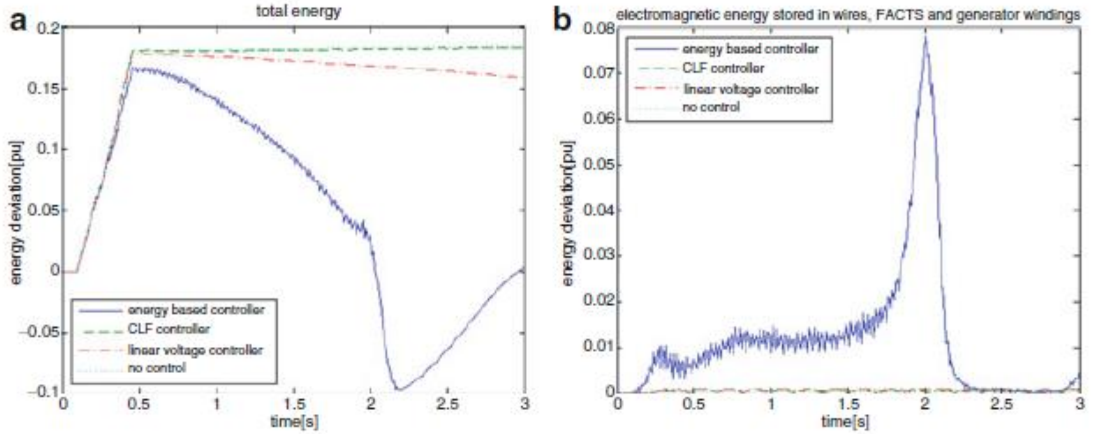
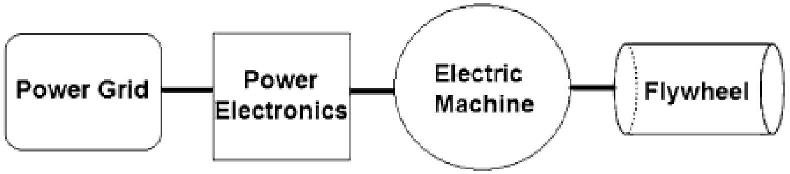


Fig. 19.15 (a) Total accumulated energy and (b) total accumulated electromagnetic energy in a system controlled by different controllers

Transient stabilization using flywheels

Concept of Sliding Mode Control Applied to a Flywheel



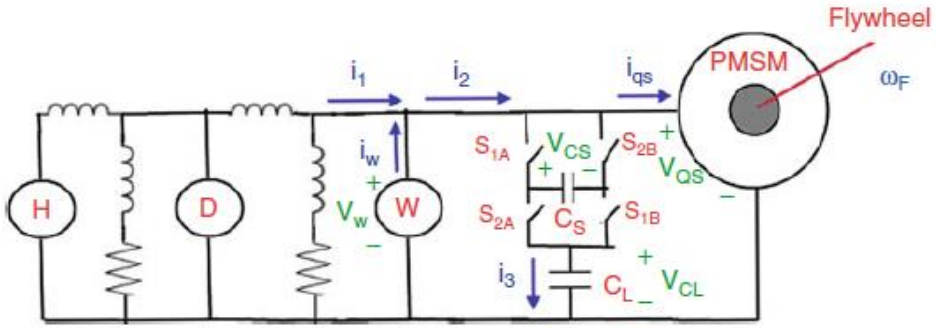


Fig. 19.34 Full diagram connecting the flywheel to Flores

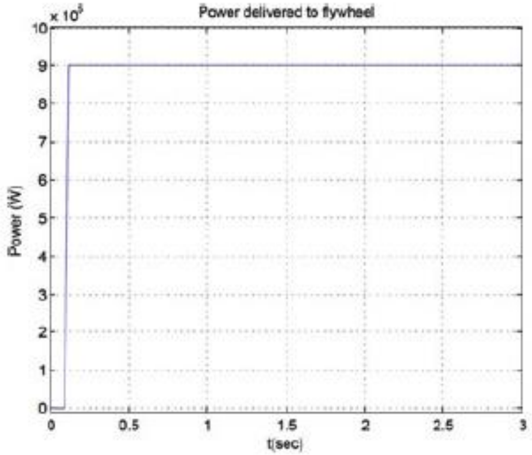


Fig. 19.32 Power delivered to the flywheel in r

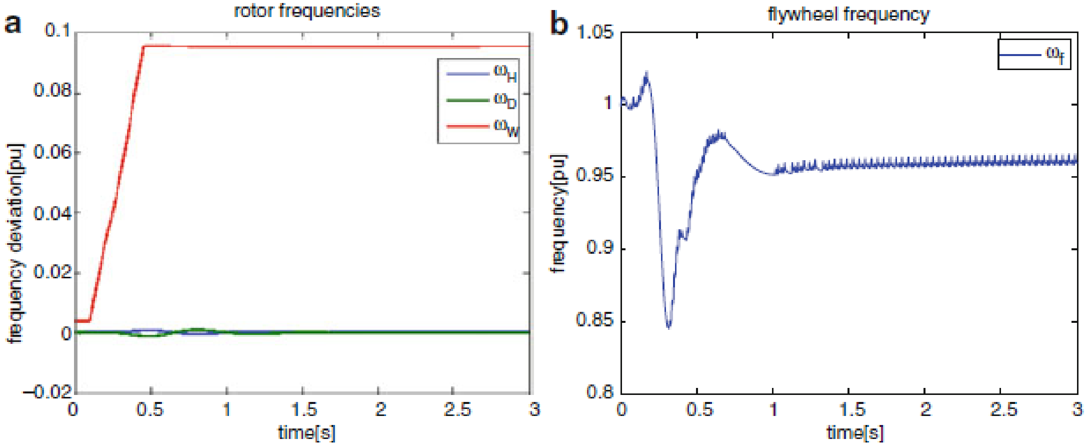
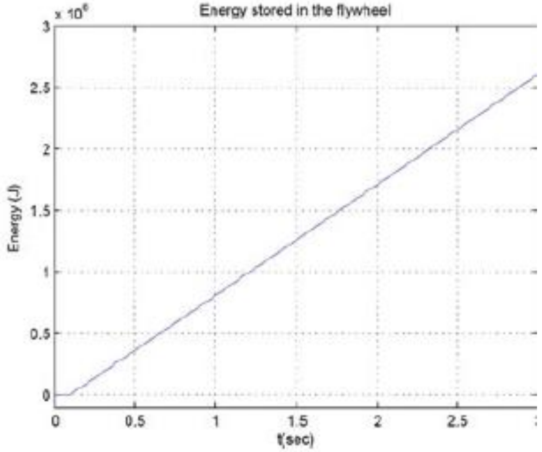


Fig. 19.35 Frequency of (a) the hydro, diesel, and wind generators, and (b) the flywheel, in the Flores system



The key role of grid reconfiguration to use DERs for reliable and resilient service

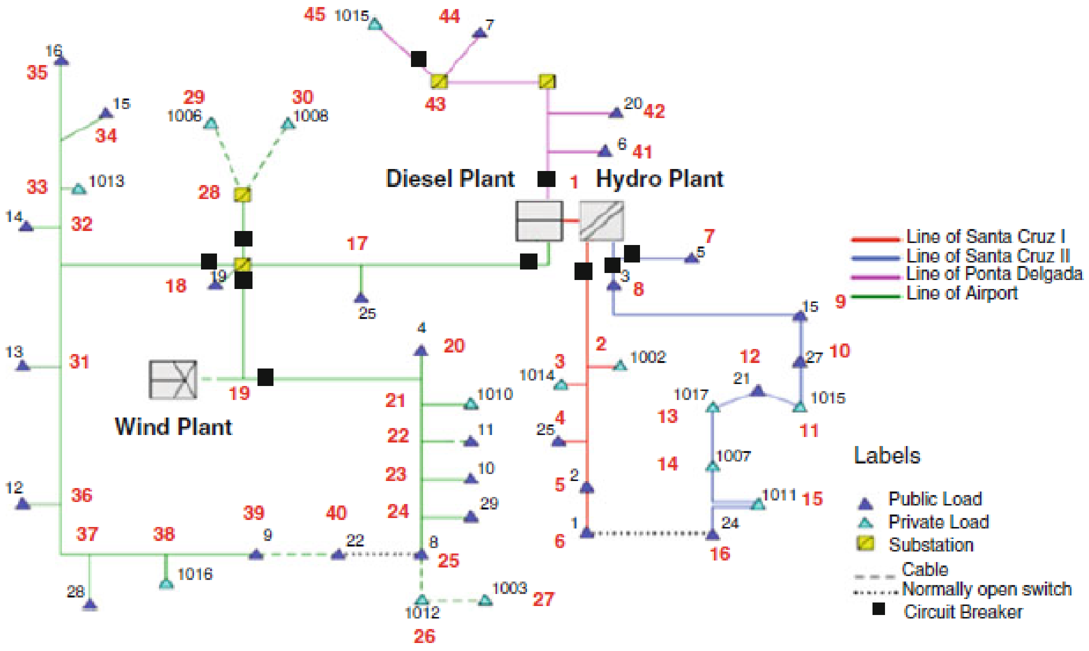


Fig. 18.1 The distribution system on the island of Flores

Toward Reconfigurable Smart Distribution Systems for Differentiated Reliability of Service

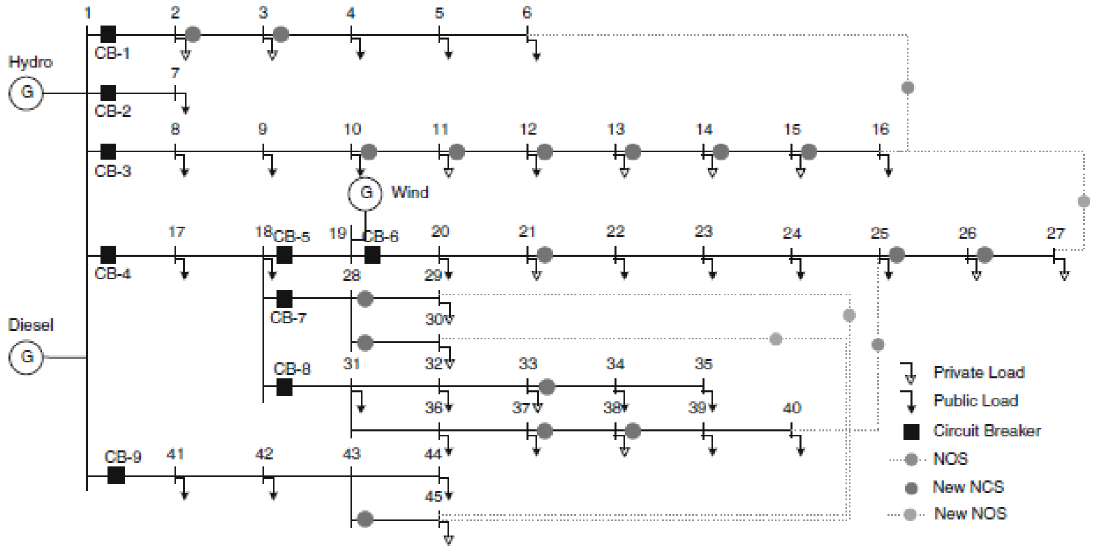


Fig. 18.4 The locations to install NCSs and NOSs

Table 18.1 Comparison of total costs between the original and modified system

	Original system	Modified system
No. of installed switches	0	20
Switch cost	0	20×$5,000 = $100,000
Total interruption cost	$67,709/year × 10 year = $677,090	$16,585/year × 10 year = $165,850
Total cost	$677,090	$265,850

Summary of lessons learned on four types of microgrids studied

- Multiple factors affecting LCOE (operating metrics, pricing, control design---must work!)
- Given performance objectives, control has the potential to reduce [CapEx, OpEx] and to increase AEP/load served

-Flores/Sao Miguel islands: 100% clean power without increasing LCOE

-Puerto Rico system: 40% increase in electricity service cost critical load served using AC OPF/distributed MPC; 50% increase in serving critical load during extreme events

-Sherif/Banshee microgrids—reduced need for batteries; no load shedding

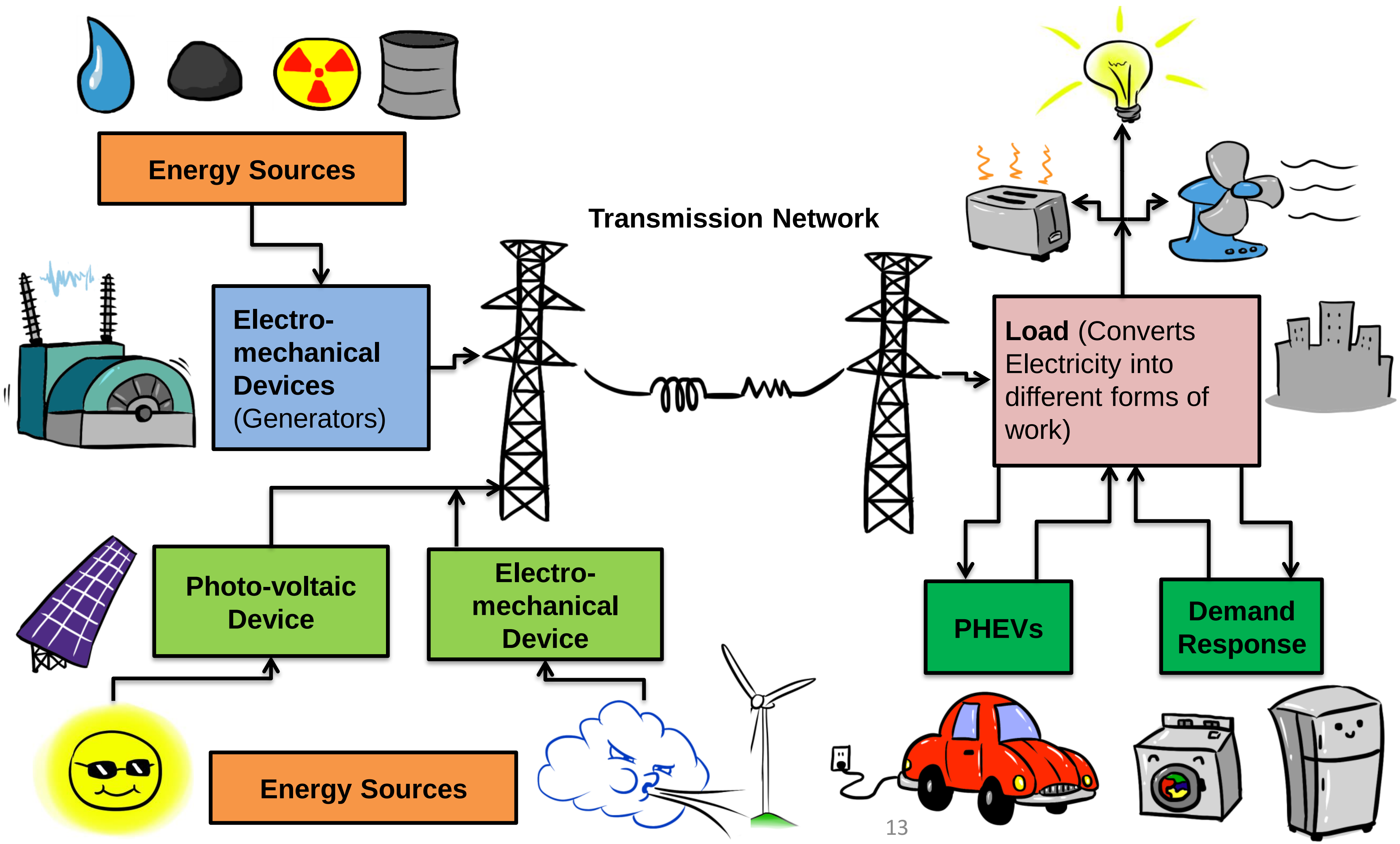
-IEEE 8,500 distribution feeder—proof of concept participation in transactive energy management while managing voltage in systems with high penetration of solar power

- Reducing CapEx: Generally less expensive storage needed; control infrastructure cost much smaller
- Reducing OpEx: Less fuel needed; less emission
- Increased AEP by the renewables; increased load served during abnormal conditions
- Basic R&D challenge: Implementation of fail-safe transparent control
- Possible way forward— systematic modeling, control and pricing innovation

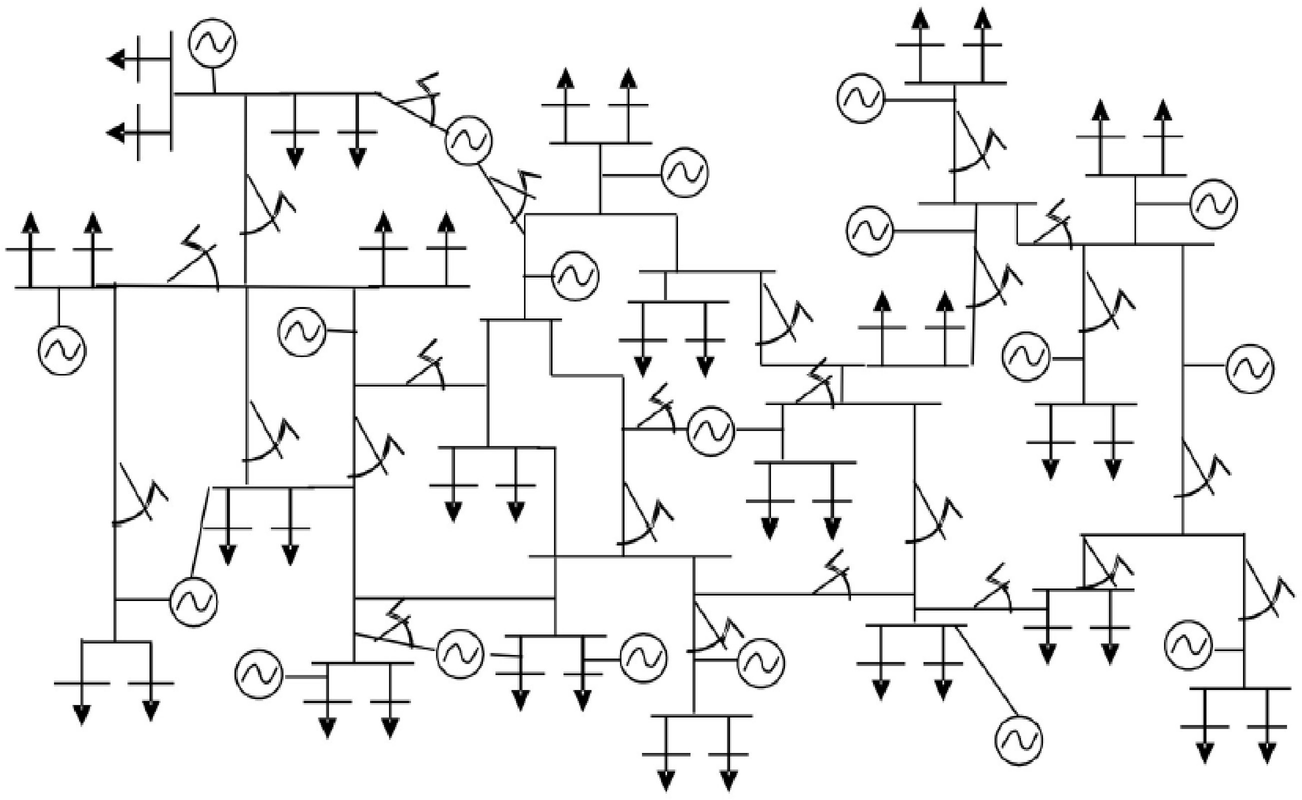
System enhancements needed—hidden traps

- ***A (microgrid controller*)**: should have adaptive performance metrics and optimize over all controllable equipment *(not the case today)*
- ***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*

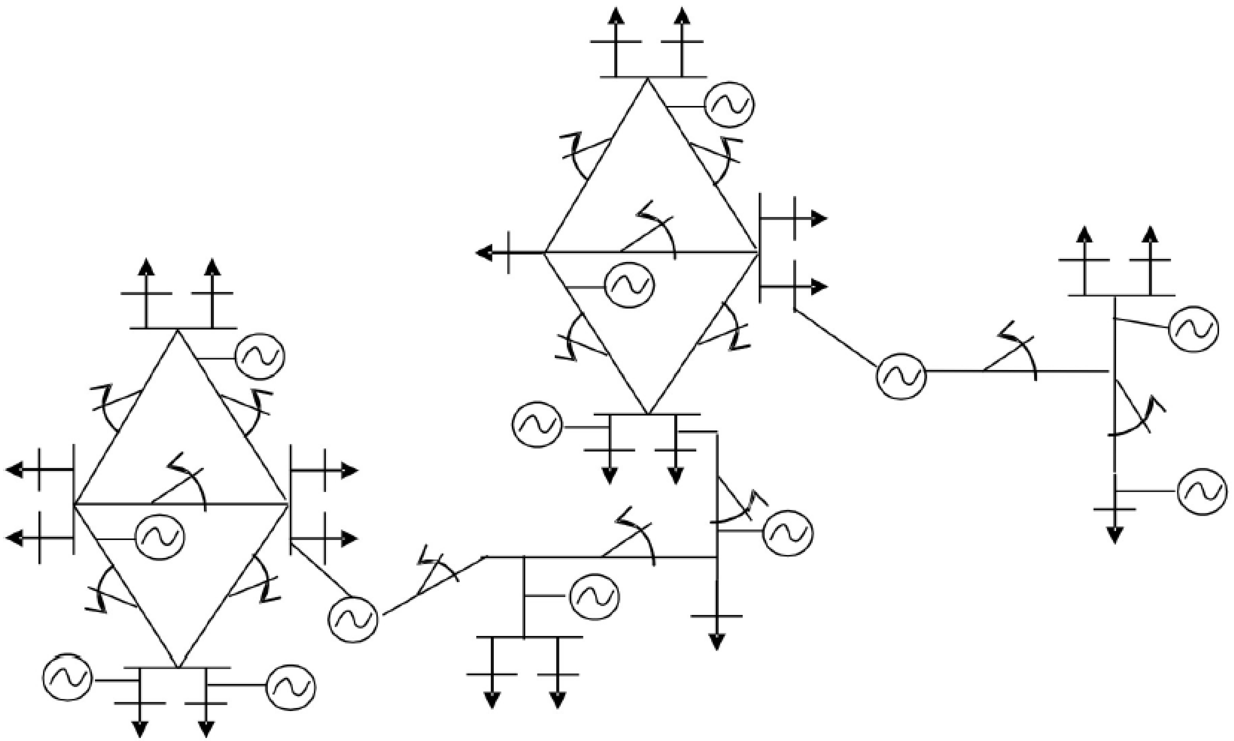
Back to first principles.. Future Power Systems-Back to Physics



Fully Distributed Small-scale Systems



Hybrid Electric Energy Systems



The main objective for understanding physics

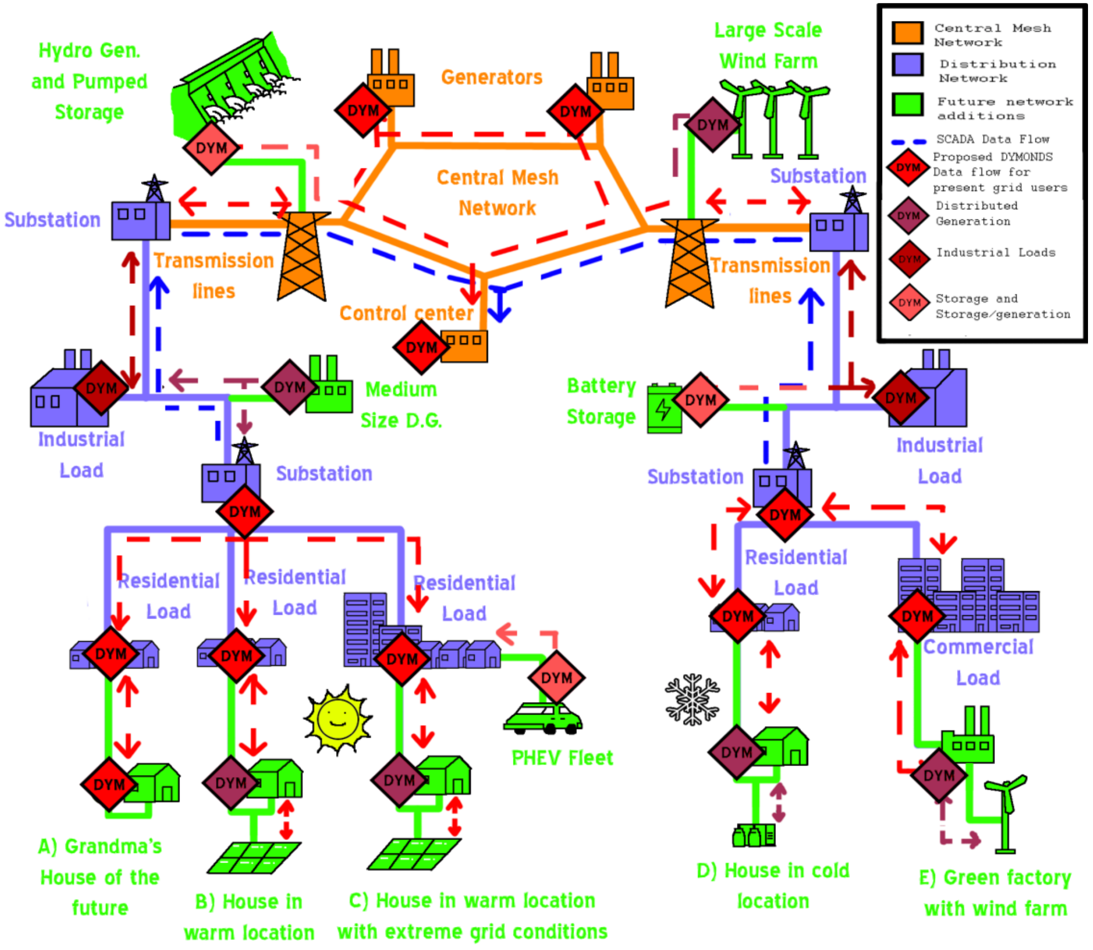
- Understanding how to think of a stand-alone component within the grid
- Understanding how to think of the interconnected power grid
- Based on this, understand the fundamental variables which

  - must be sensed and controlled at the component level

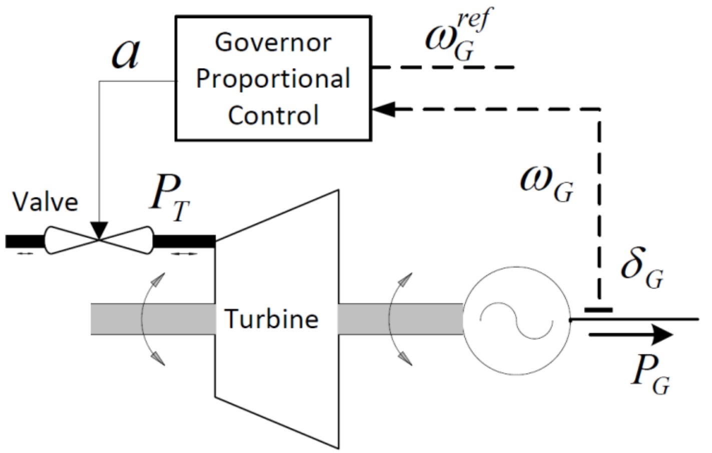
  -must be exchanged between the components

  -make the case for physics-based processing underlying ``smarts" design

Physics-based information processing for smarts



Linearized droop for G-T-G set – Motivation for SoA modeling of microgrids



$$\omega_G = -\sigma P_G + (1-\sigma K_d)\omega_G^{ref}$$

$$\sigma = \frac{r}{rK_d + K_t}$$

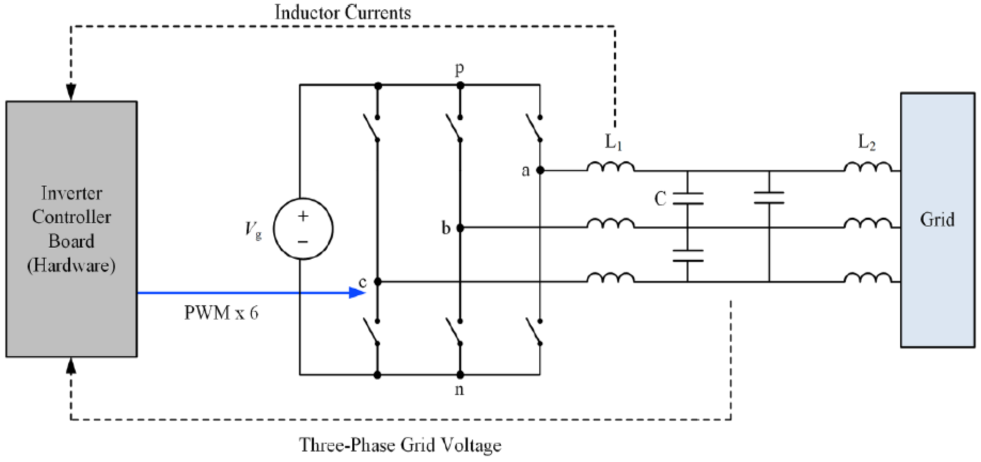


Fig. 9 *Scheme of the inverter power stage and control board*

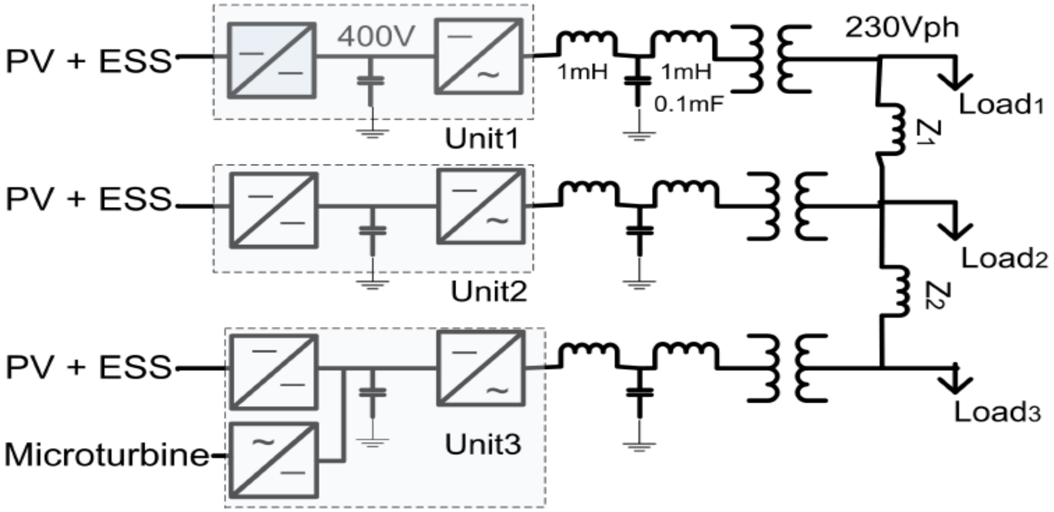
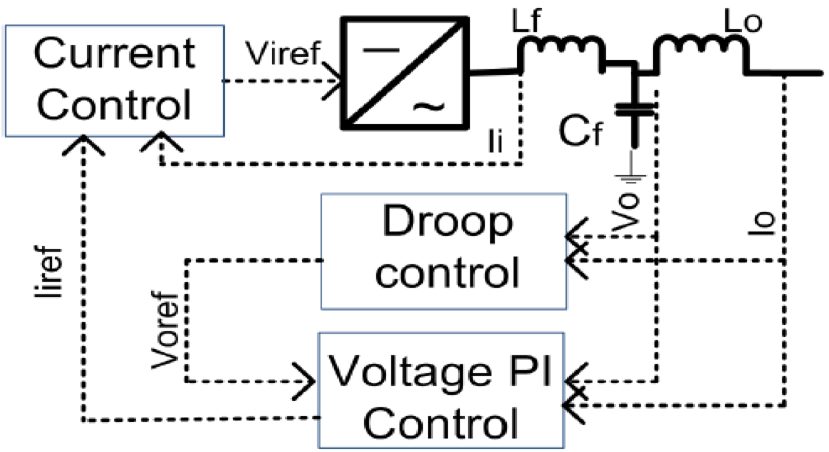


Fig. 1: Schematic of the autonomous microgrid.



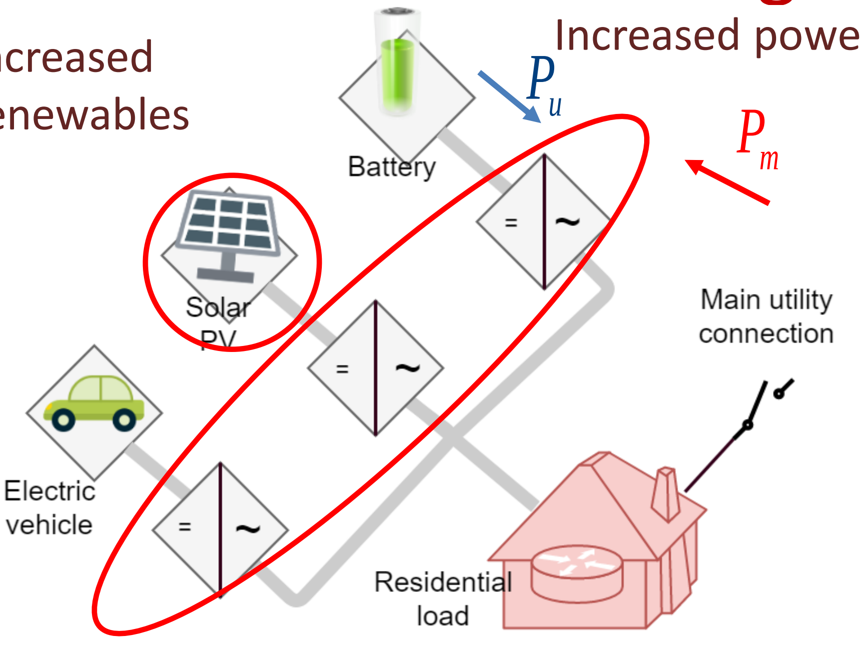
(a) Inverter control scheme.

Basic R&D control challenge:

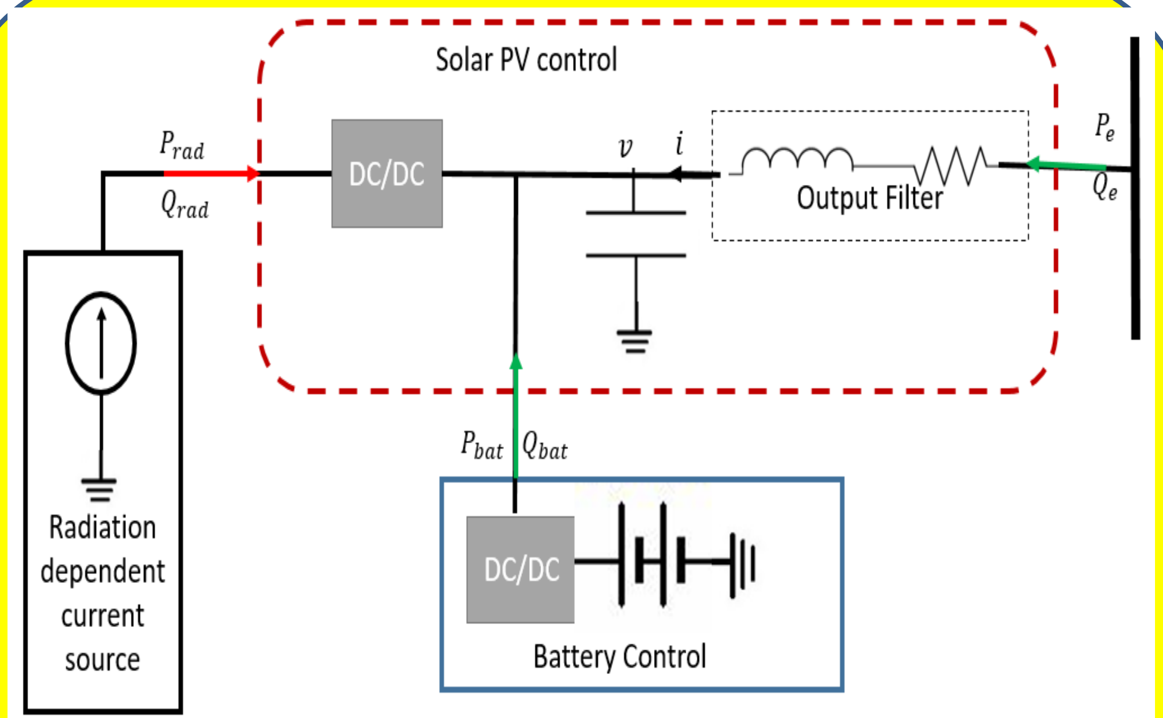
Overcoming complexity of modeling and control

Increased renewables

Increased power electronics



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!!!

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

Example of a physics-based solar PV droop

Energy Space Model:

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

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

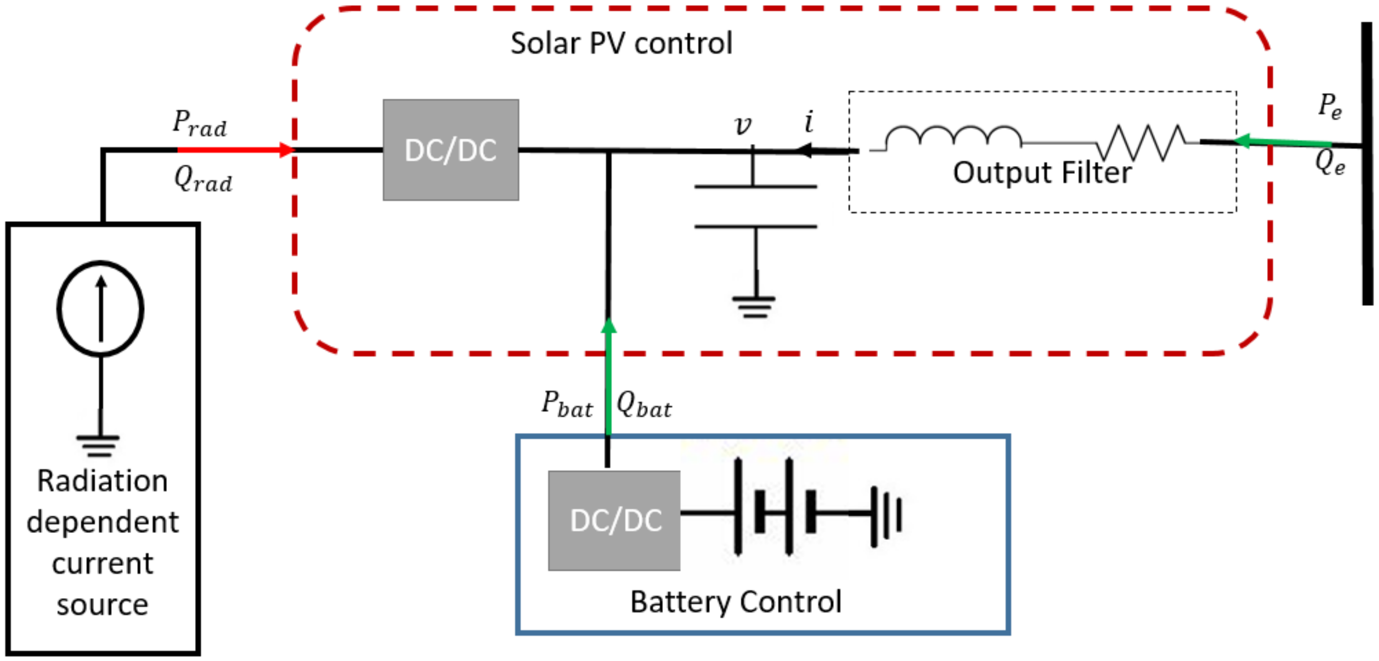
Here, $E(t) = \frac{1}{2}Li(t)^2 + \frac{1}{2}Cv(t)^2$

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



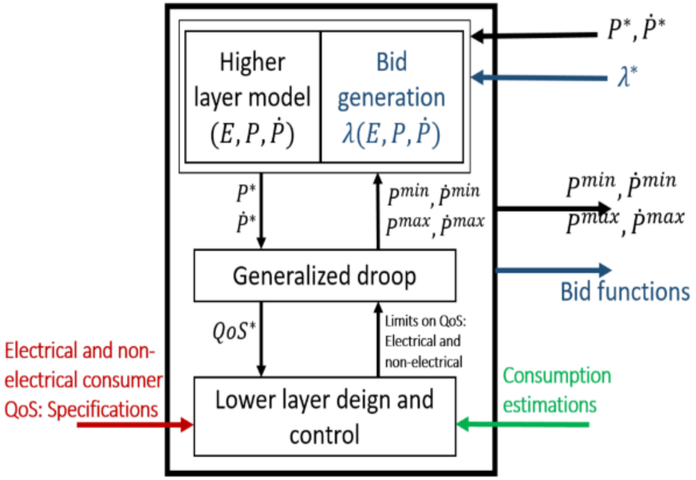
Over much longer time scale identified by sample number k, it is possible to obtain the following relation (assuming converter efficiencies are all 100%)

PV Energy-conversion Droop Relation:

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

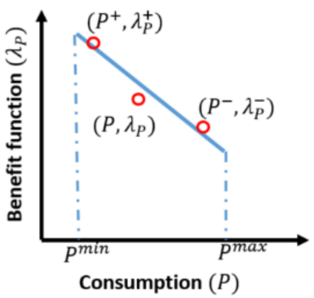
DER Energy Conversion Droop Relation: $\Delta P[k] = \sigma\Delta W[k]$

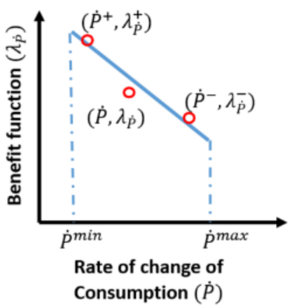
Component specifications (load)

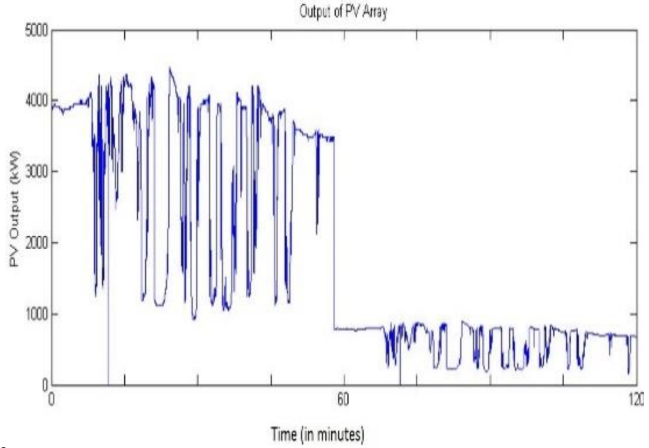


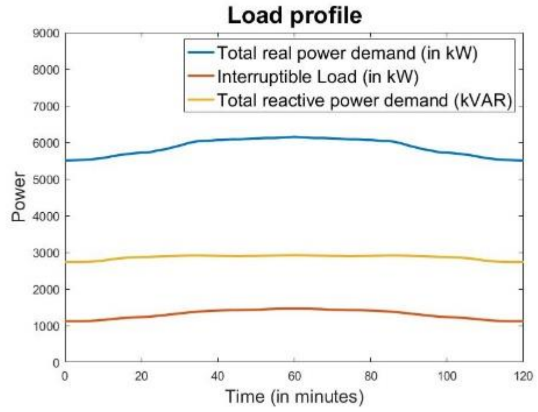
Type of Load	Minimum Loading				Maximum Loading			
	Real Power		Reactive Power		Real Power		Reactive Power	
	Absolute Demand (in MW)	% of total Demand	Absolute Demand (in MW)	% of total Demand	Absolute Demand (in MW)	% of total Demand	Absolute Demand (in MW)	% of total Demand
Priority	0.99	36.14	0.44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

Input-output in energy space



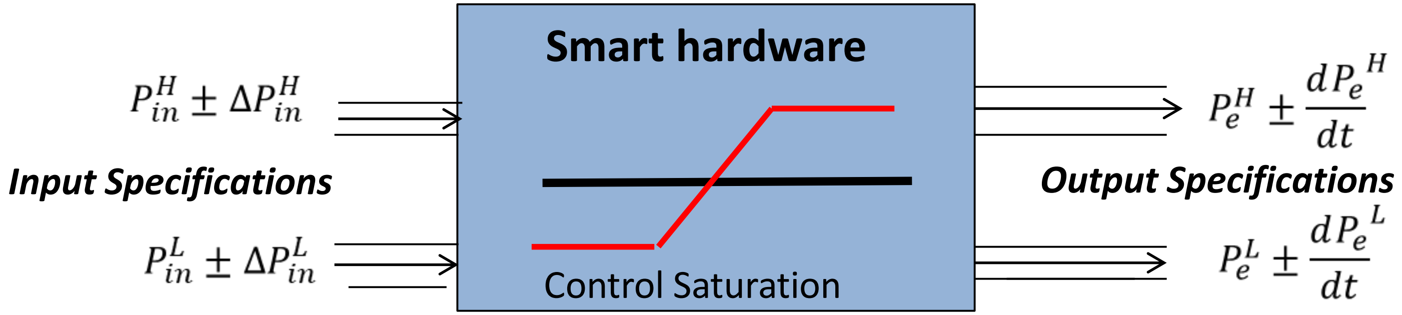






Economic and physical characterization

Unified component specifications and interaction conditions in energy space for stable/feasible operations [5,6,7,9]



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)

Theoretical foundations for three control co-design principles

- **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.**

Concluding thoughts

- Iterative control co-design has a great potential for enabling microgrids to meet both technical and economic performance. It should be considered seriously, but unified modeling and problem posing is required in context of microgrids and other electric energy systems.
- Today's approach to managing difficult conditions is to either build more expensive batteries or to pre-program protection for load shedding for the case scenarios considered to be the most challenging. This is both expensive, can lead to un-necessary load shedding and does generally not guarantee stable/feasible operation when system inputs vary continuously.
- Research up to date shows the need to enhance control in particular using concepts based on modeling in energy space.
- Minimal coordination should use AC Optimal Power Flow for scheduling both real power and reactive power/voltage dispatch.

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THANK YOU