Cyber-Secure Dynamic Monitoring and Decision Systems (DyMonDS) for Emerging Microgrids: Challenges and Opportunities

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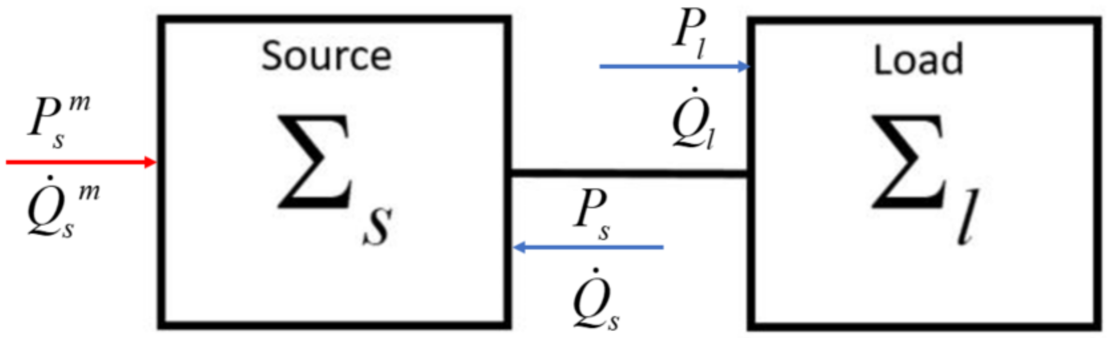
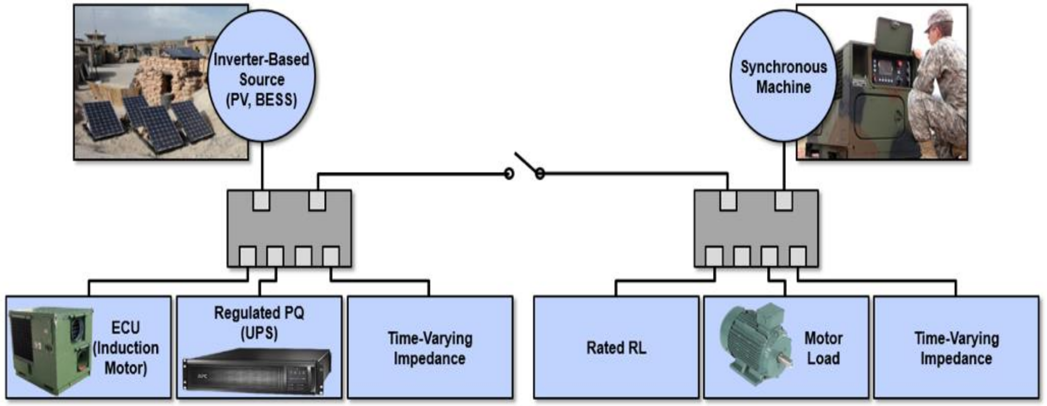
Energyville Workshop

September 19,2023

https://microgrid-symposiums.org/energyville-2023/

Synergic problems in terrestrial, naval and aircraft microgrids





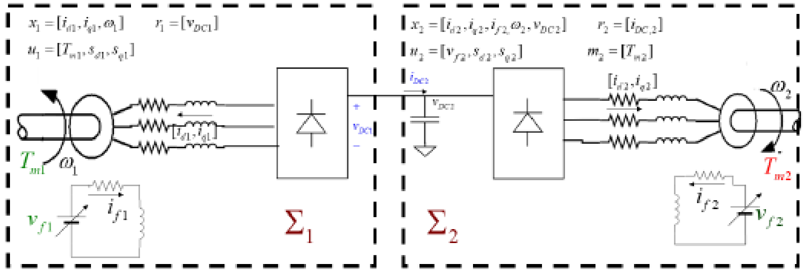
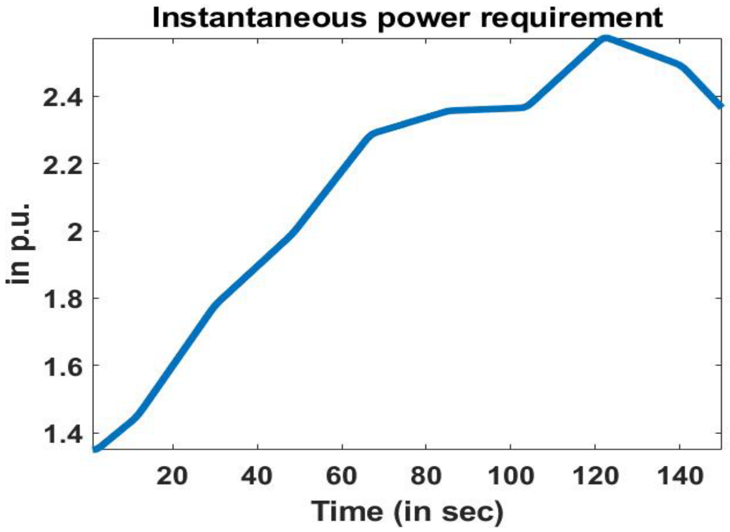


Figure 3: An example TeDP system comprising synchronous machines connected through an AC-DC-AC converter



Ilic, M. (2021). Microgrid Operation and Control: Challenges and expected functionalities. *IEEE Electrification Magazine*, *9*(3), 65-74.

Challenges and opportunities

- ***Technical challenges:*** Design and control to enable stable operation for wide ranges of input variations and topological changes.
- ***Business challenges***: Maximize DER deployment, while minimizing load shed, and need for expensive fast storage.
- ***Technical opportunities***: Major innovation at value.
- ***Business opportunities:*** ***a) for utilities*** *(high tech business of electricity services at value);* ***b) for vendors*** *(massive development and deployment of smart hardware and system cyber software);* ***c) for electric energy users*** *(choice at value).*
- ***Societal opportunities:*** *Clean, secure electricity service at choice and value.*

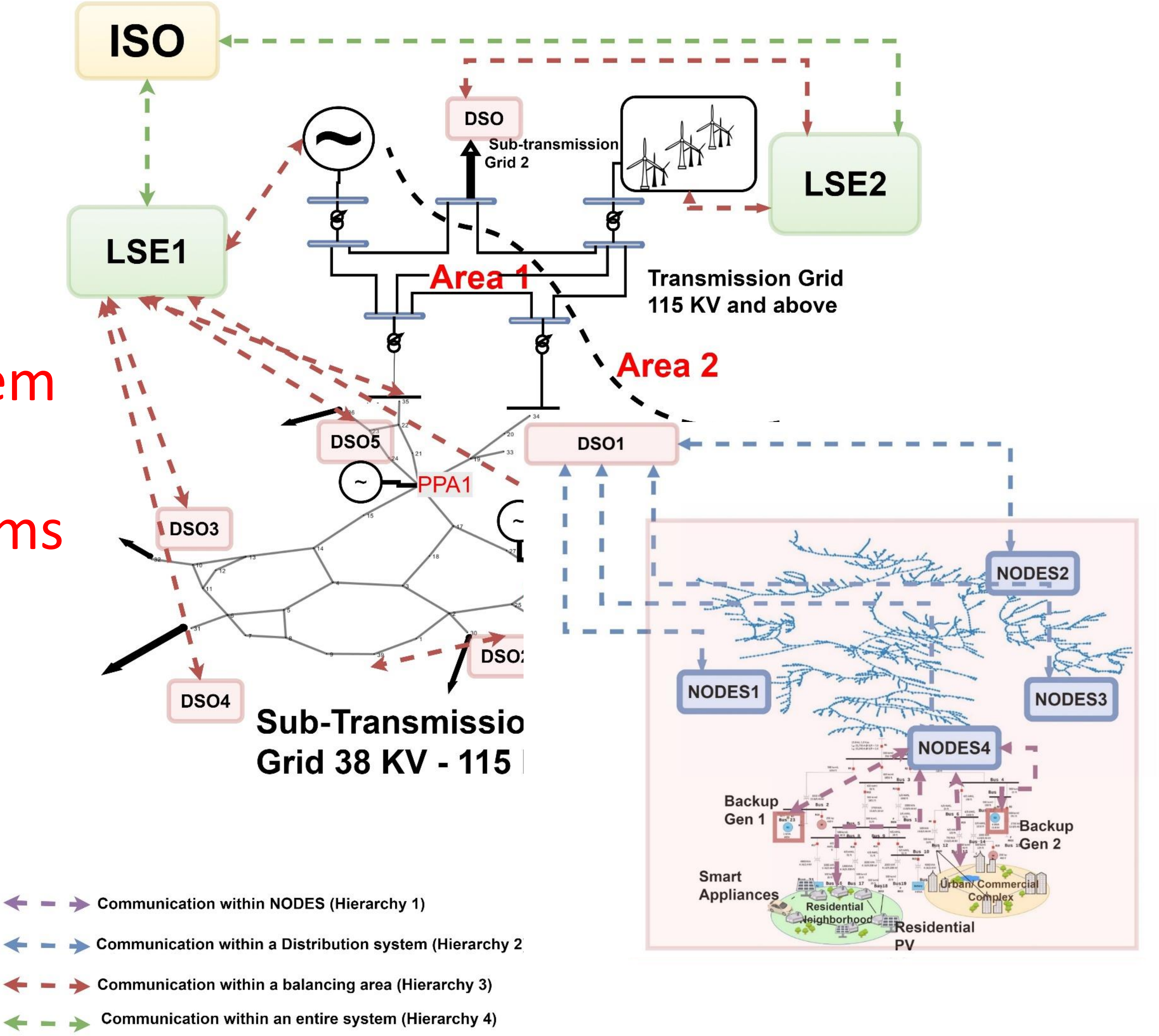
Ilic, M. D. (2016). Toward a unified modeling and control for sustainable and resilient electric energy systems. *Foundations and Trends® in Electric Energy Systems*, *1*(1-2), 1-141.

Outline

- Microgrids studied (Azores Islands, Puerto Rico; distribution feeders (Sheriff, Banshee; large continental IEEE 8500 bus grid); TeDPs for hybrid aircrafts
  - Scaled up in size; diverse resources (wind, PVs, CHPs, storage), loads (priority, controlled, uncontrolled), grid topologies (stand-alone; reconfigurable 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

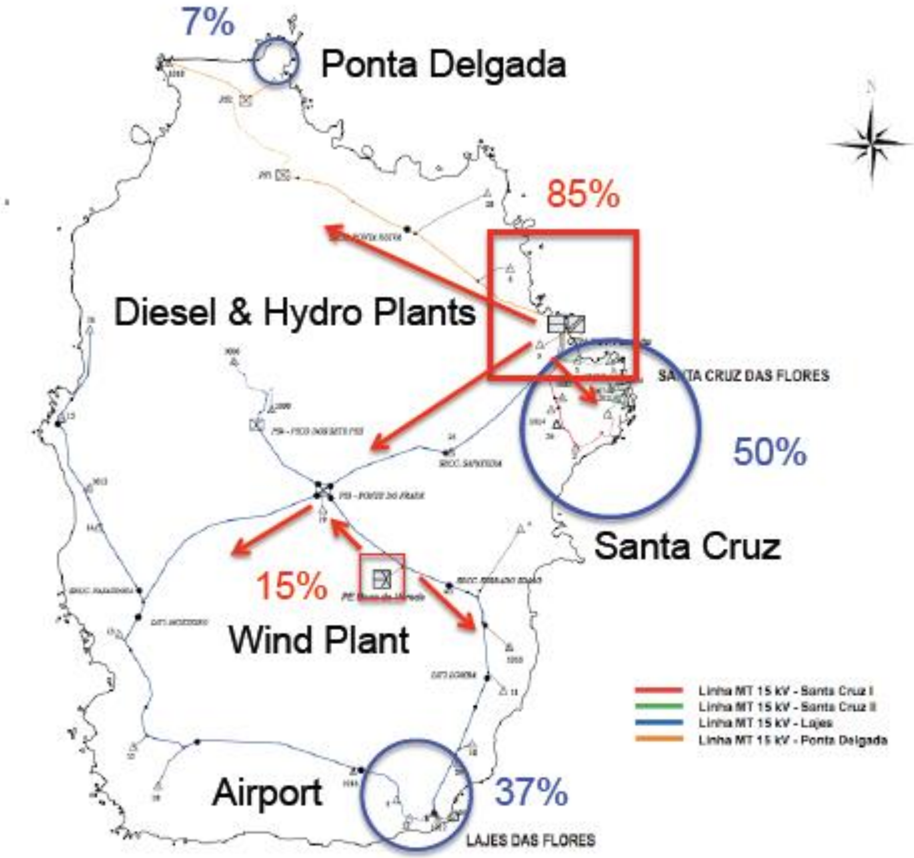
Multi-layered interactive system

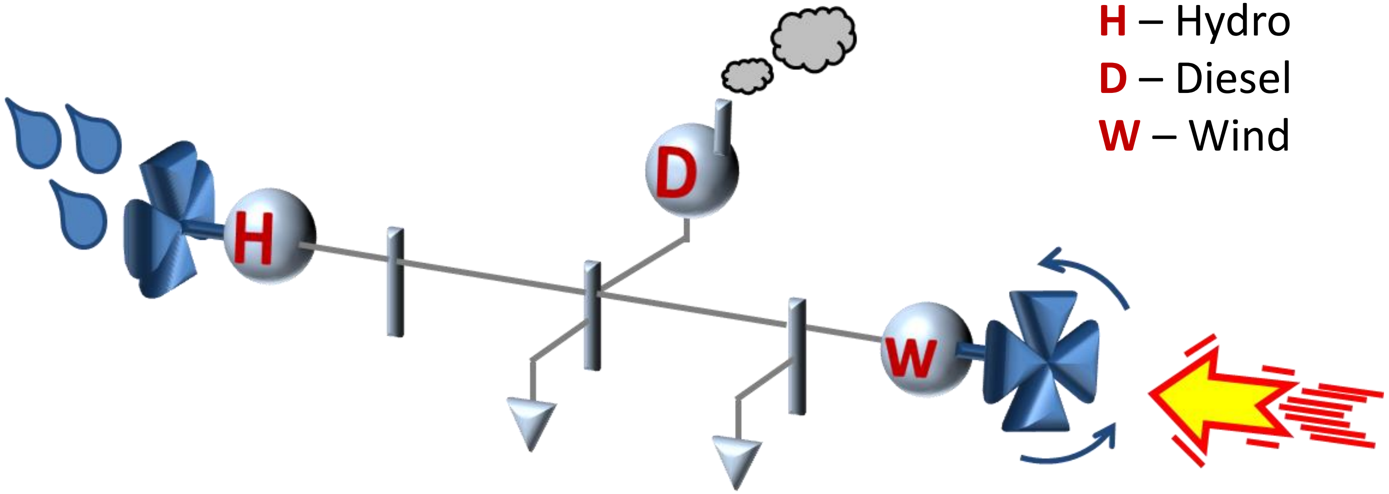
``Seams” problems



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.

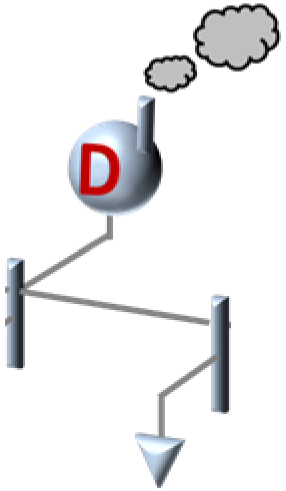
Flores Island Power System-Typical micro-grid of the future*



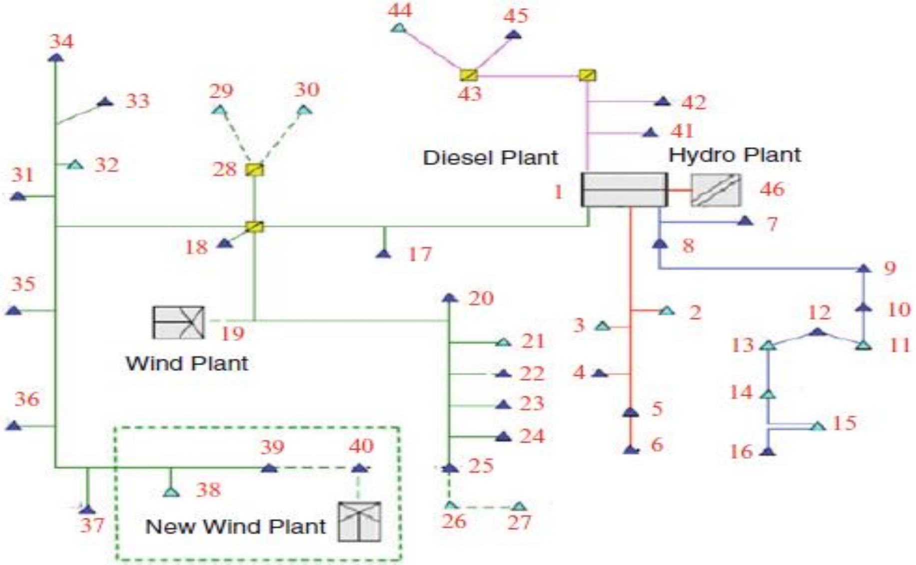


H – Hydro
D – Diesel
W – Wind

From

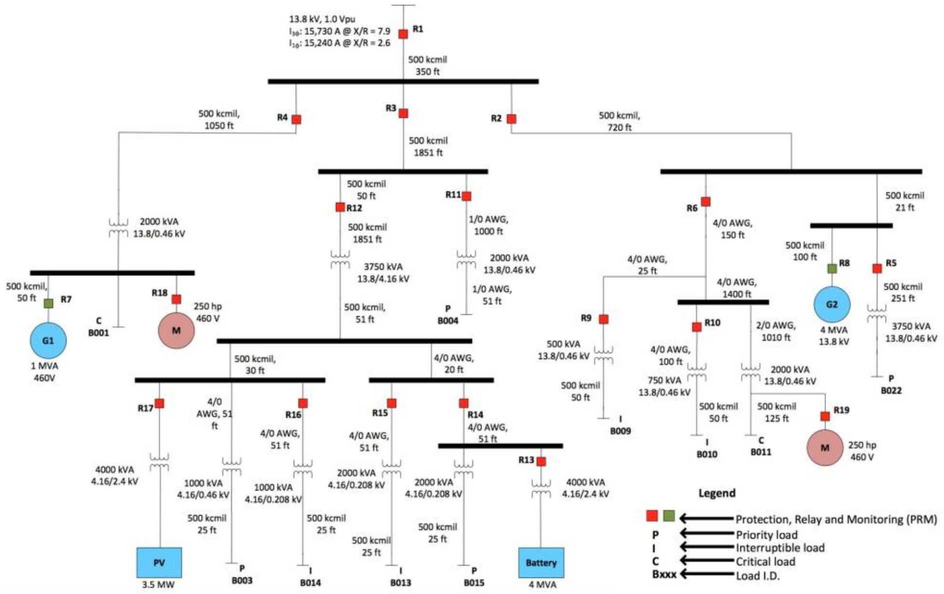


To?



*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.

Complexity of emerging microgrids



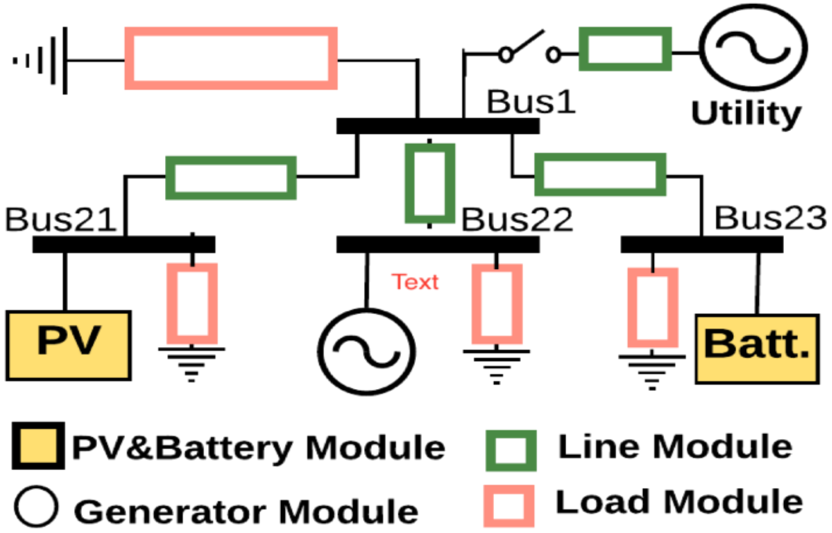


Fig 1 Diverse loads, different priorities/dynamics

Fig 2 Heterogenous resources

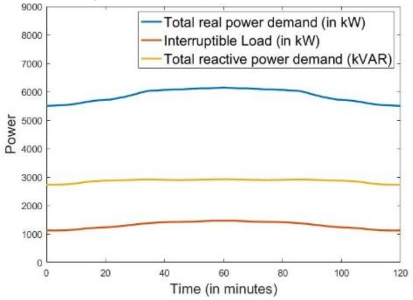
Sheriff microgrid– IEEE test system

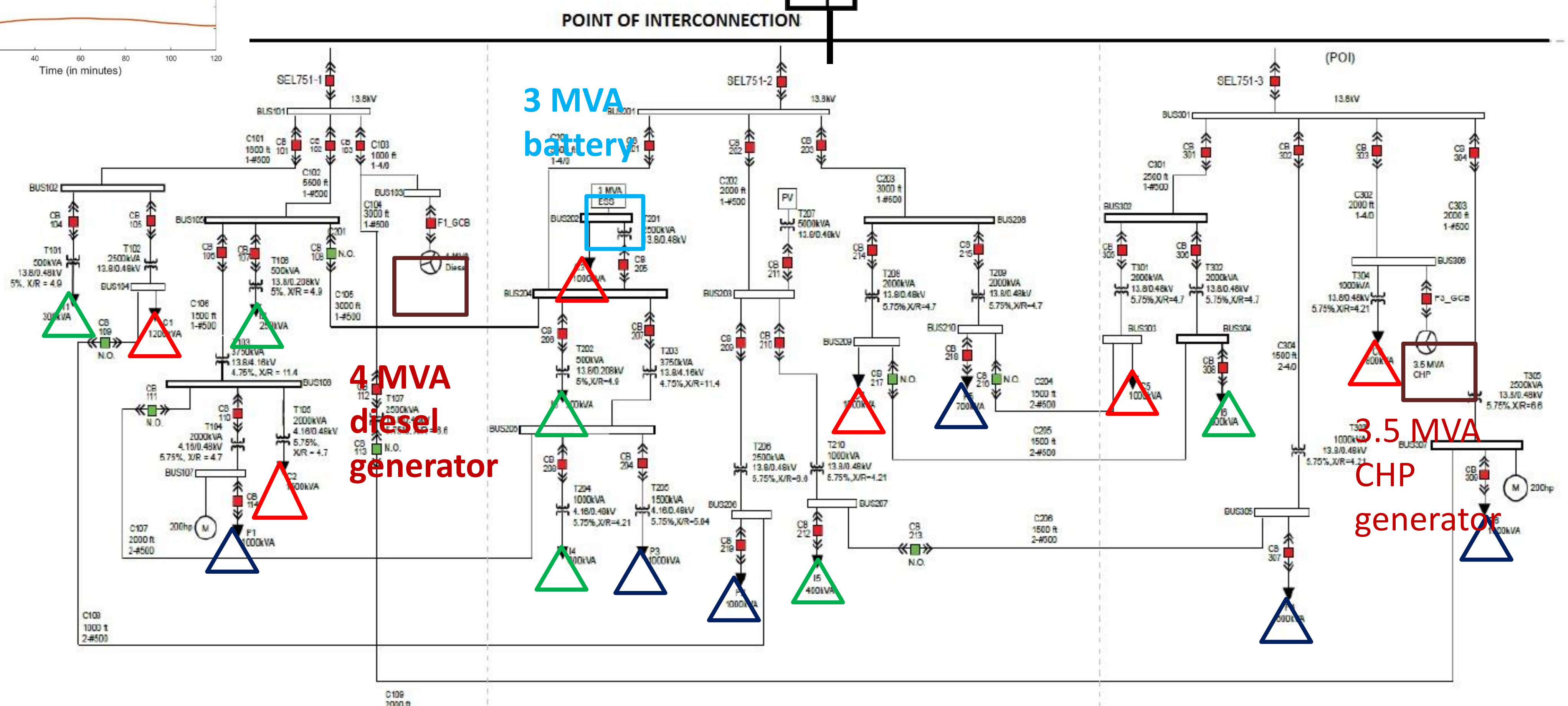
Limpaecher, E., R. Salcedo, E. Corbett, S. Manson, B. Nayak, and W. Allen. "Lessons learned from hardware-in-the-loop testing of microgrid control systems." In CIGRE US National Committee 2017 Grid of the Future Symposium, 2017.

Ilić, Marija, Rupamathi Jaddivada, and Xia Miao. "Modeling and analysis methods for assessing stability of microgrids." IFAC-PapersOnLine 50.1 (2017): 5448-5455.

Real world feeder – Banshee distribution system

Sample Load Profile

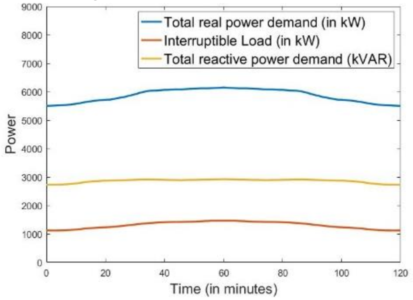


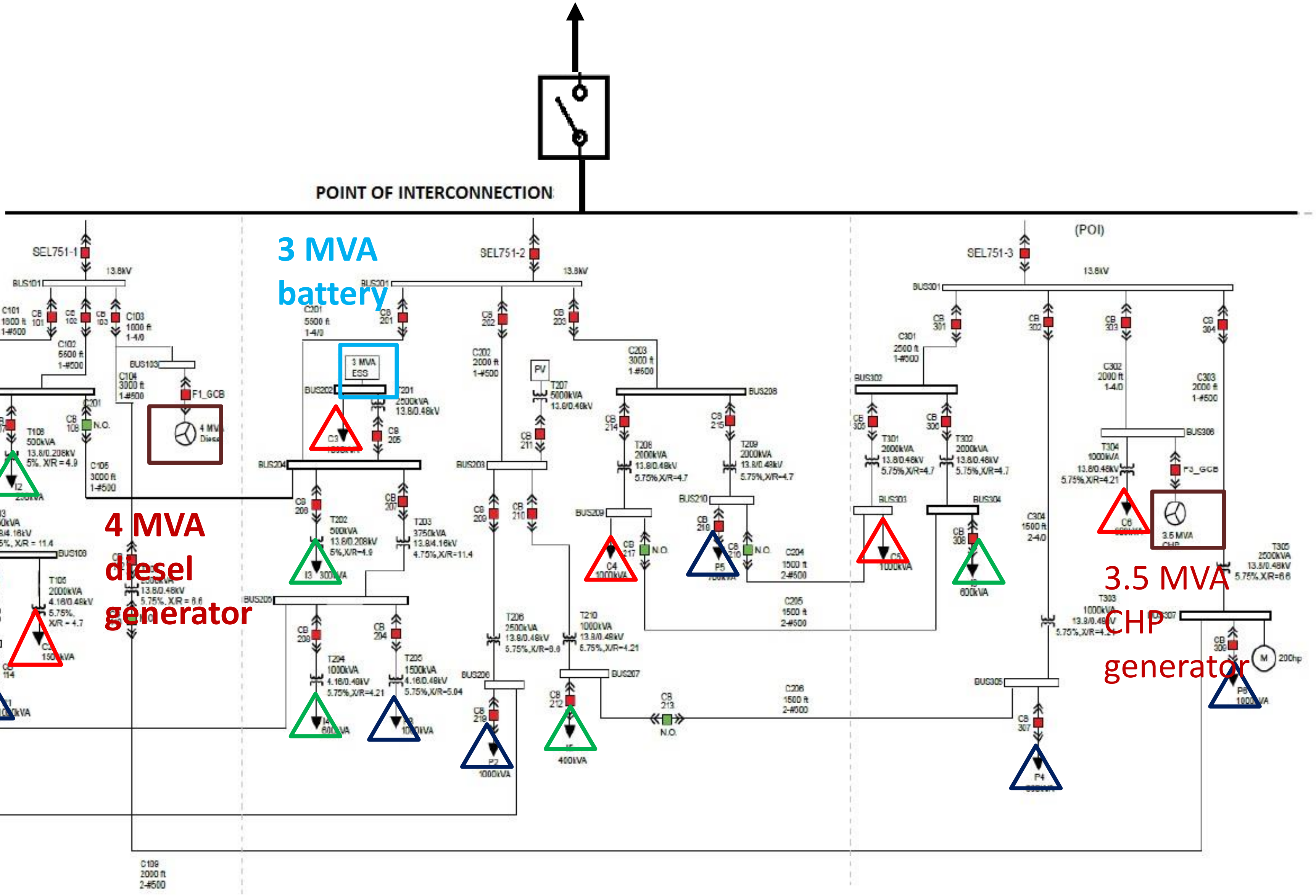


Salcedo, R., Corbett, E., Smith, C., Limpaecher, E., Rekha, R., Nowocin, J., ... & Manson, S. (2019). Banshee distribution network benchmark and prototyping platform for hardware-in-the-loop integration of microgrid and device controllers. The Journal of Engineering, 2019(8), 5365-5373.

Effect of new technologies

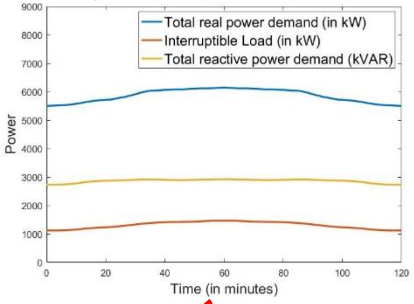
Sample Load Profile



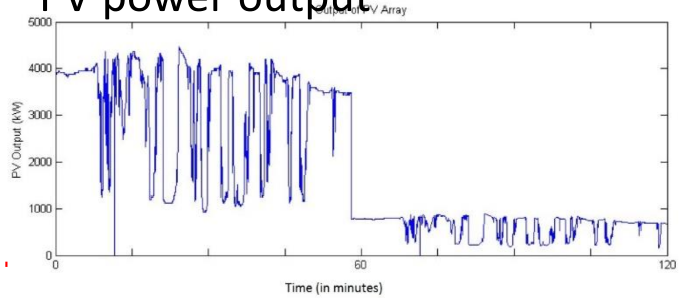


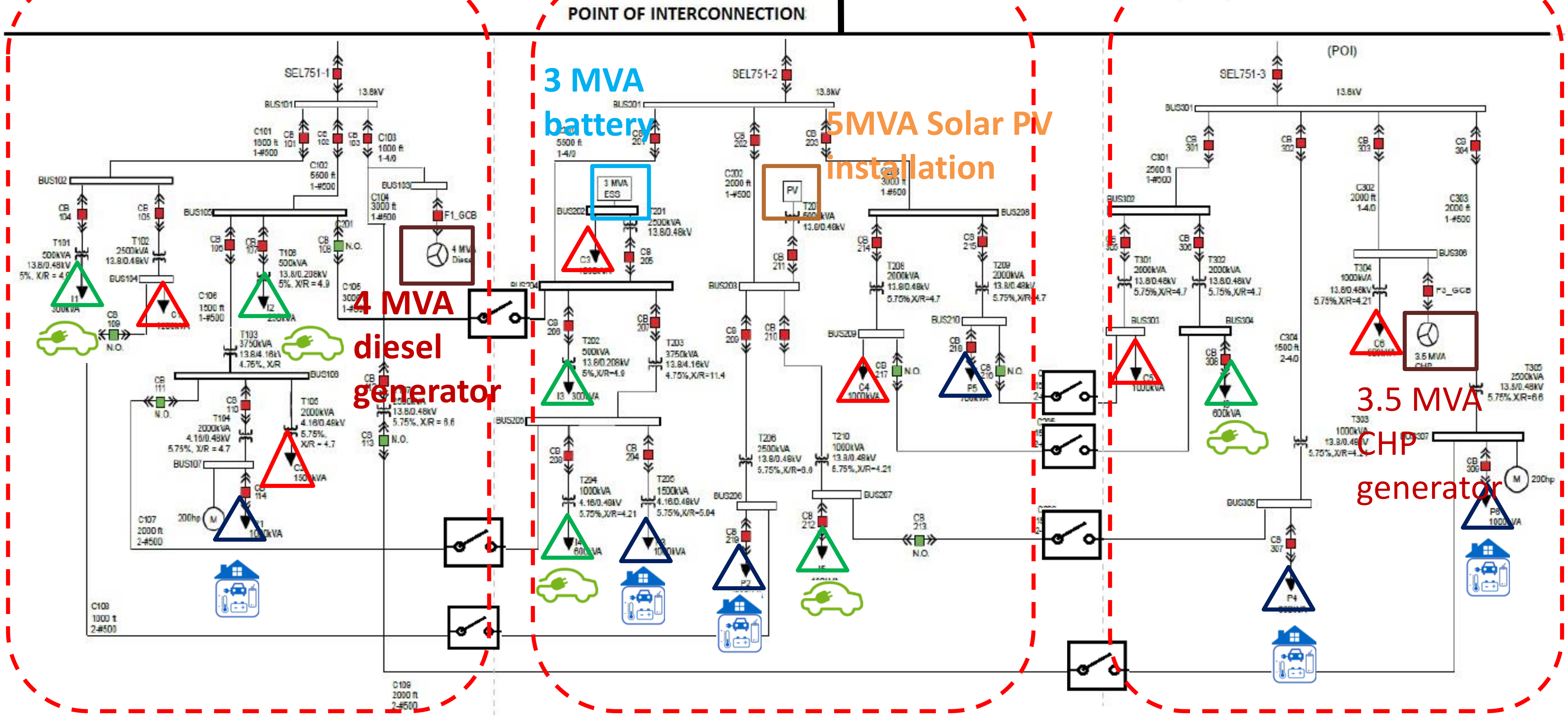
Evolution of such feeders

Sample Load Profile



PV power output





CRITICAL LOADS

PRIORITY LOADS

Interruptible LOADS

Existing and emerging challenges/needs

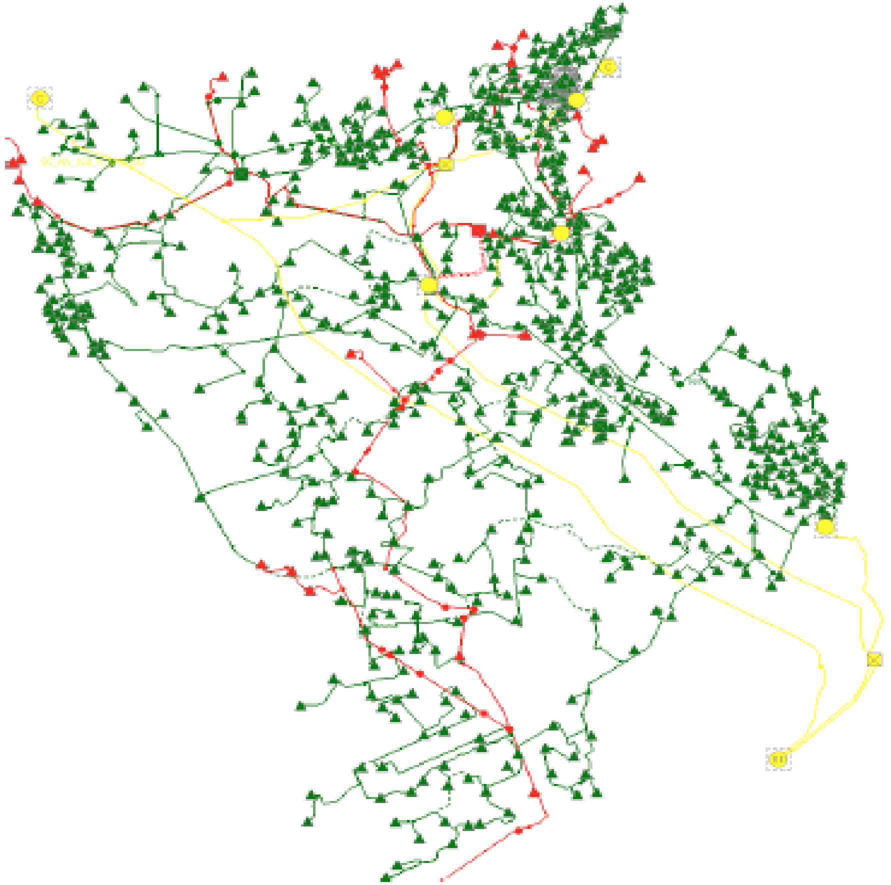


Figure 1 – Multi-level geographical network representation (sub-transmission at 60kV in yellow, and distribution at 30kV in red and 15kV in green).

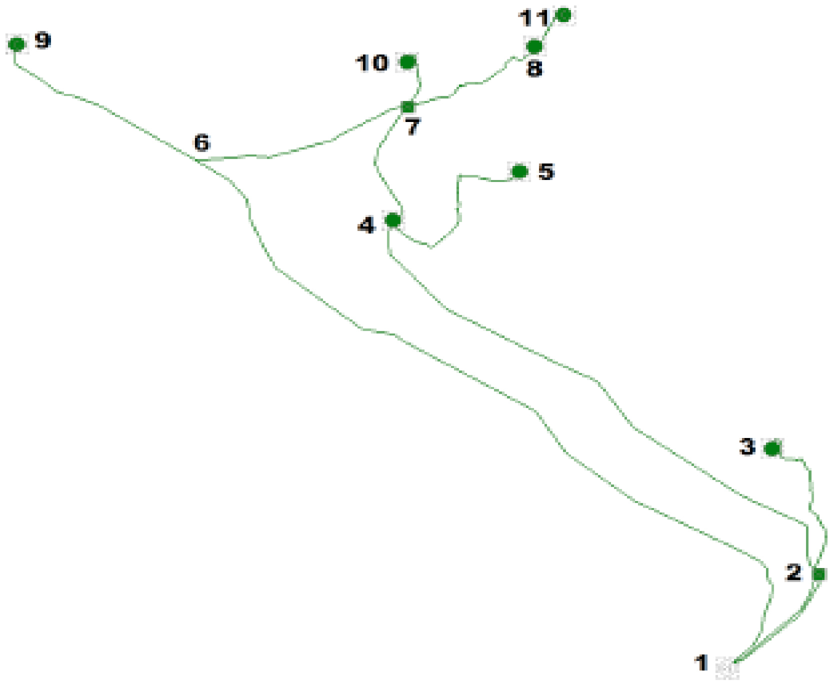


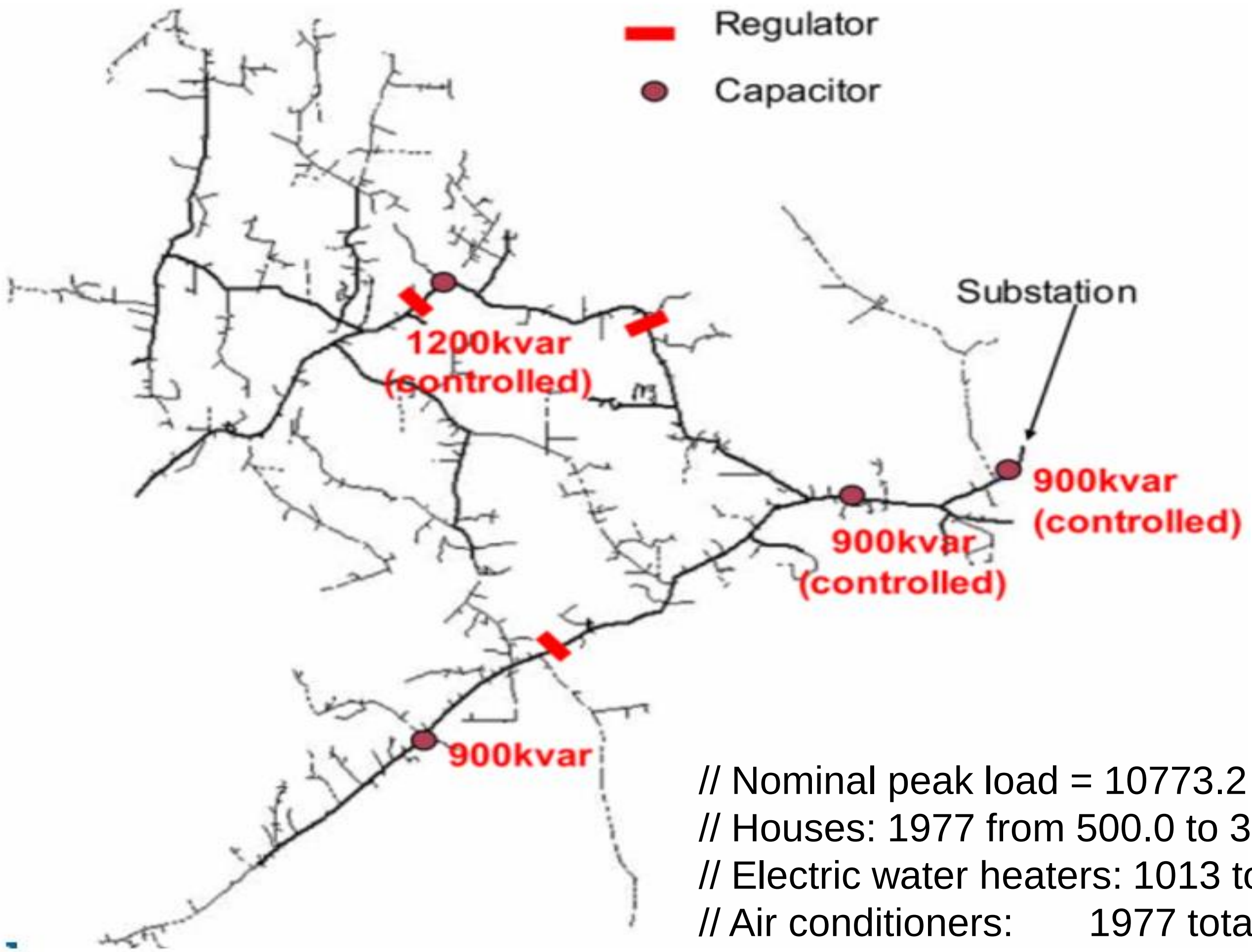
Figure 2 – Sub-transmission 60kV geographical network representation with current filter enabled (green means currents are below cable rating)

HOW TO ZOOM INTO CERTAIN LEVEL AND TAKE INTO CONSIDERATION THE EFFECT OF MANY OTHERS ?? MULTI-LAYERED NETWORKS

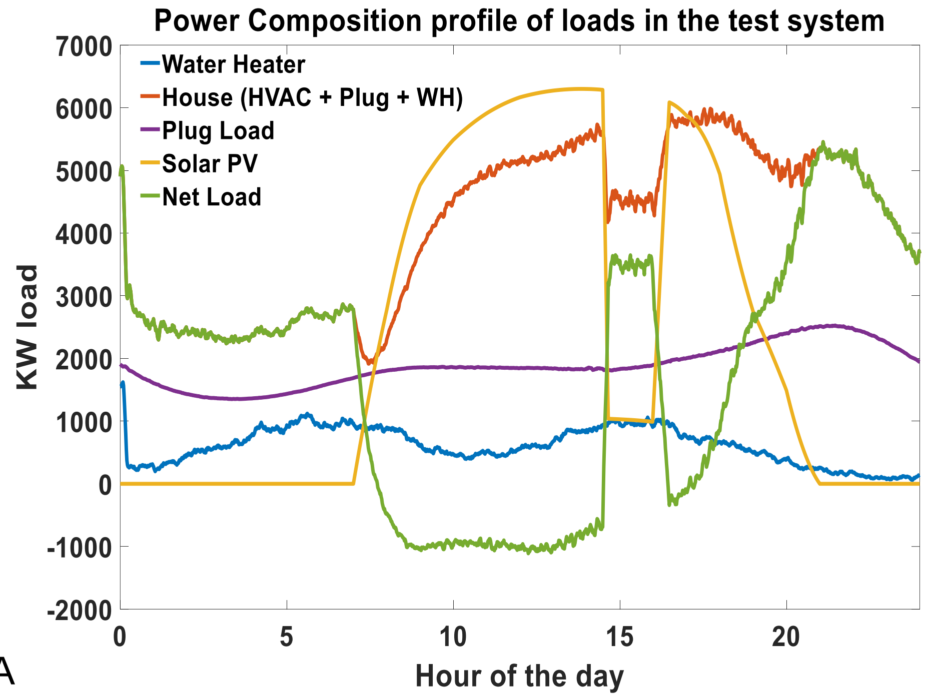
Ilic, M., Joo, J. Y., Carvalho, P. M., Ferreira, L. A., & Almeida, B. (2013, August). Dynamic monitoring and decision systems (DYMONDS) framework for reliable and efficient congestion management in smart distribution grids. In *2013 IREP Symposium Bulk Power System Dynamics and Control-IX Optimization, Security and Control of the Emerging Power Grid* (pp. 1-9). IEEE.

MANAGING COMPLEXITY? SCALING UP?

8,500 test system



BASELINE INPUTS (EXOGENEOUS)



// Nominal peak load = 10773.2 + j2700.0 kVA
// Houses: 1977 from 500.0 to 3500.0 sf, total area 3941782 sf
// Electric water heaters: 1013 totaling 4574.7 kW
// Air conditioners: 1977 totaling 26150.6 kW
// Solar: 1777 totaling 6755.2 kW
// Storage: 857 totaling 4285.0 kW
// Water heater load is resistive
// HVAC load ZIP=0.2,0.0,0.8 with variable power factor as input
// (the fan load ZIP=0.2534,0.7332,0.0135 and pf=0.96)
// Non-responsive ZIP load is input all constant current, pf=0.95

Holmberg, David, Martin Burns, Steven Bushby, Tom McDermott, Yingying Tang, Qiuhua Huang, Annabelle Pratt et al. "NIST Transactive Energy Modeling and Simulation Challenge Phase II Final Report." NIST special publication (2019).

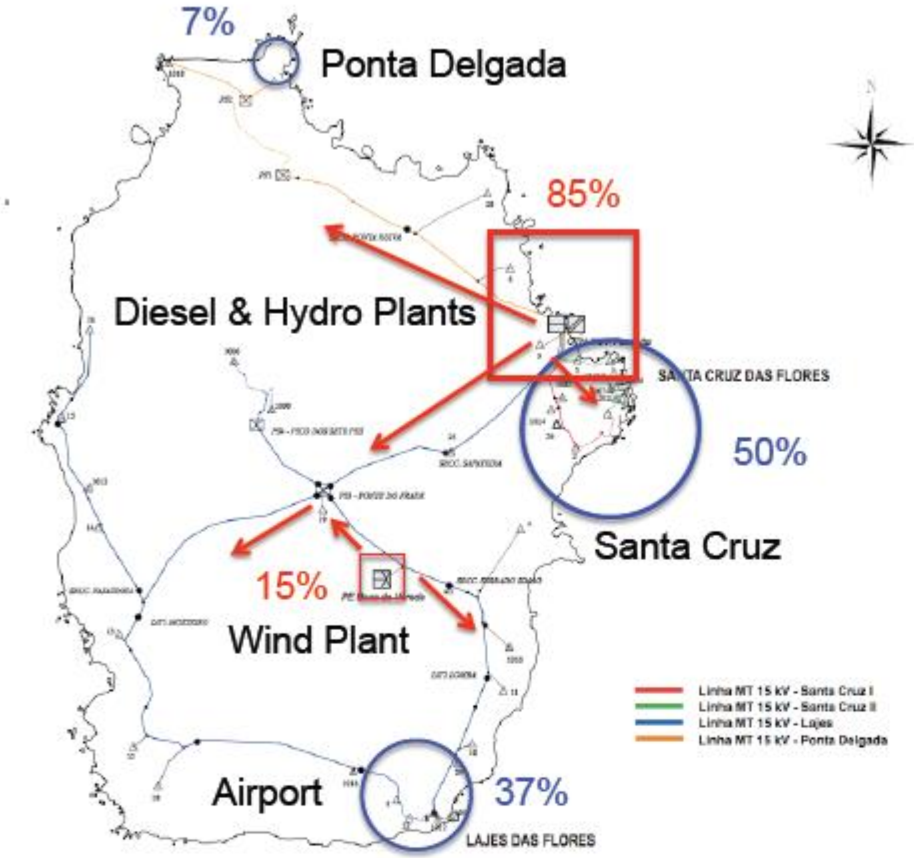
Overall technical challenge

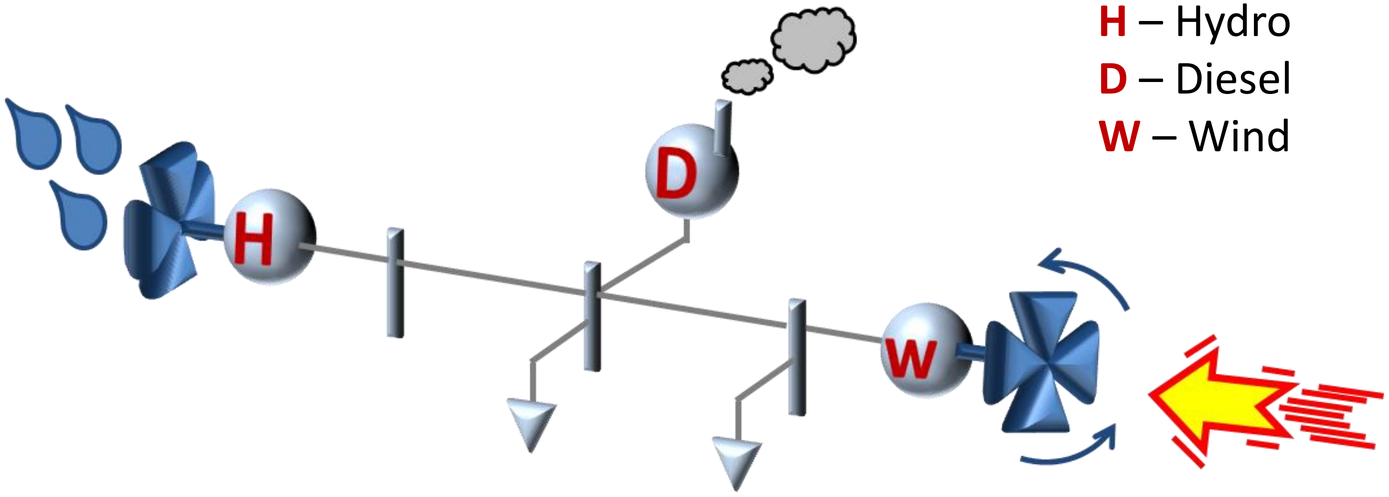
- **Need systematic tools to assess operating problems**

--***when and why the grid may not work—could trigger protection and cascading failures*** (power cannot be delivered within given constraints; conditions sensitive/unstable w/r to input disturbances and model uncertainties)

- **Must design control to manage technical problems**
  - enhanced hierarchical control; fail/safe distributed coordination; protocols for coordination
  - primary control capable of meeting specifications

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





H – Hydro
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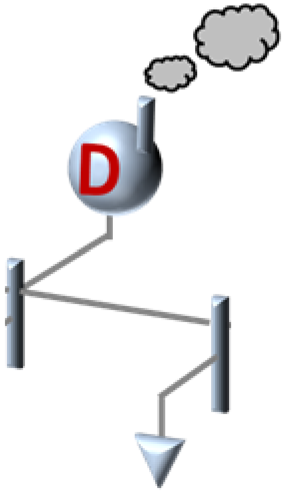
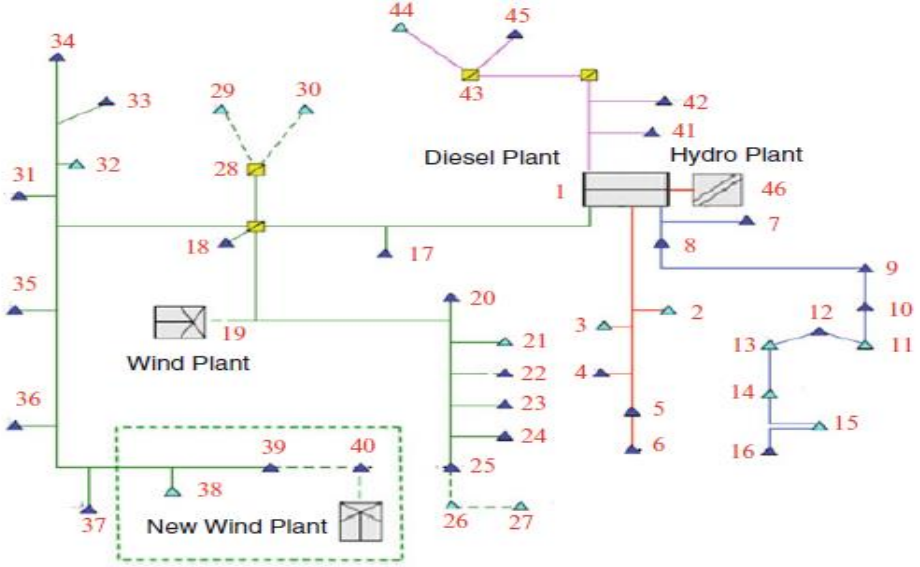


To?



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Effects of microgrid controller (AC OPF-based)

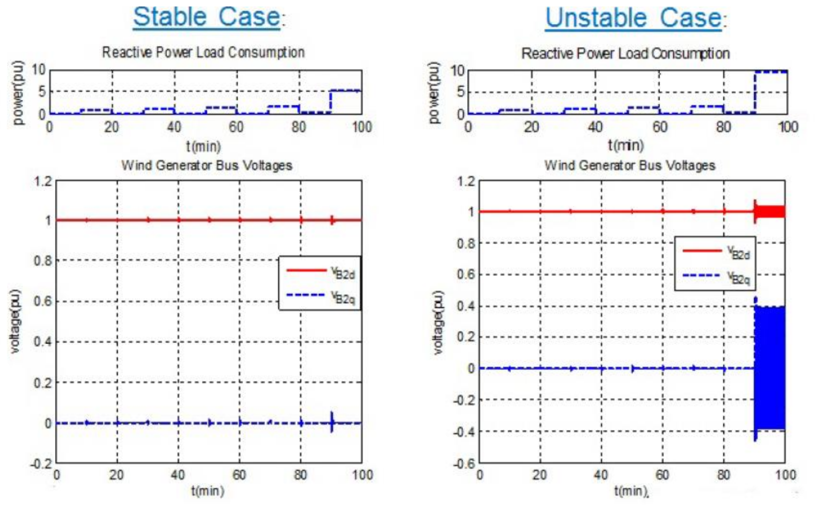
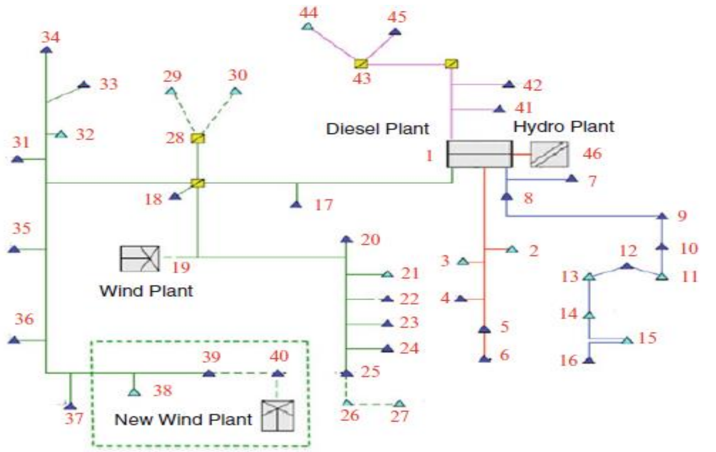


Fig. 33. Simulation results demonstrating that the reactive power set points are crucially important to the dynamic stability of the system



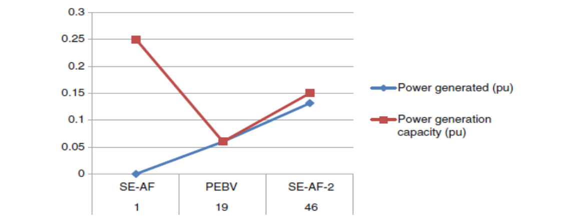


Fig. 13.3 Geographical distribution of optimal generation in Flores, wind power O&M cost 88 $/MWh

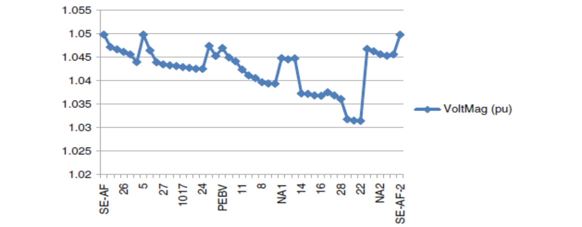


Fig. 13.4 Geographical distribution of optimized voltages in Flores, wind power O&M cost 88 $/MWh

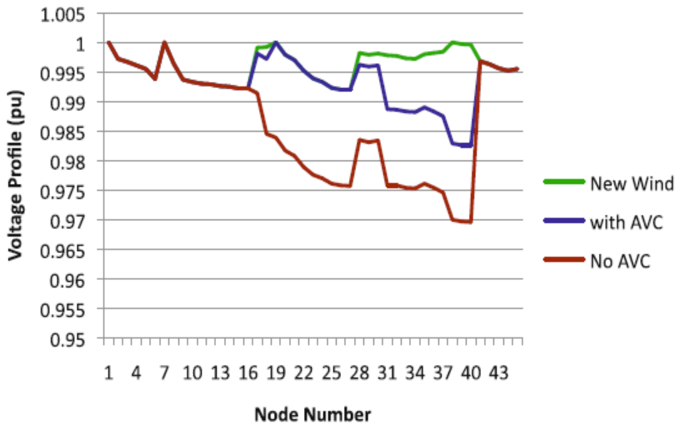


Fig. 12.6 Voltage profile of the island in three different scenarios

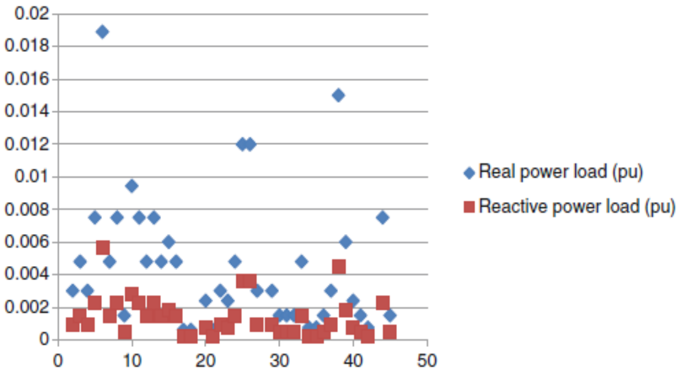


Fig. 13.2 Geographical distribution of load in Flores; the *x*-axis is the bus number 1–46; the *y*-axis is load in per unit (pu)

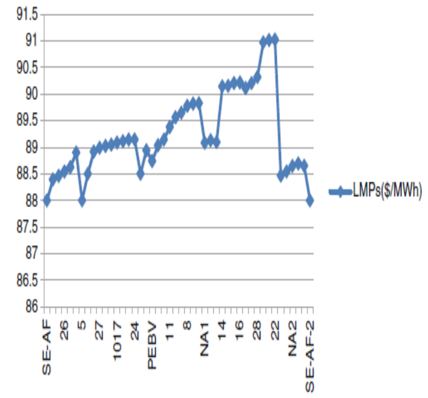


Fig. 13.5 Geographical distribution of LMPs in Flores; wind power O&M cost 88 $/MWh

Potential to add PVs and support them with EVs

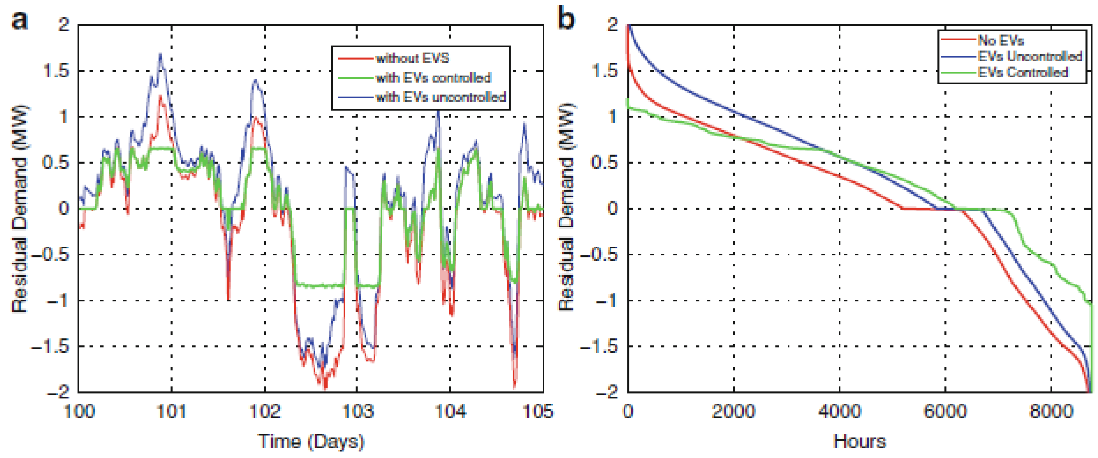


Fig. 11.9 Residual demand in three scenarios for the moderate wind and solar scenario and 1,000 EVs in a 5-day spring period (a) and the load duration curves (b)

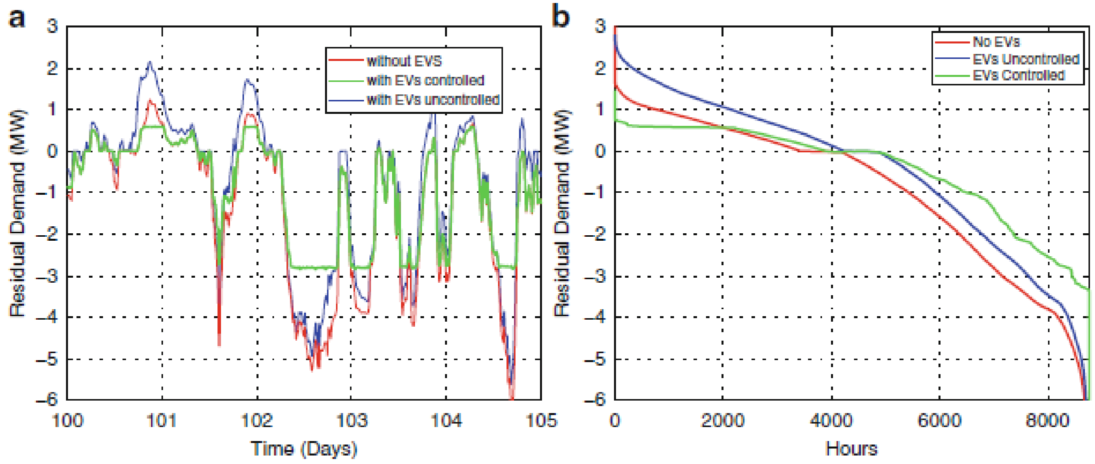


Fig. 11.11 Residual demand for the maximum wind and solar scenario and 2,000 EVs in a 5-day spring period (a) and the load duration curves (b)

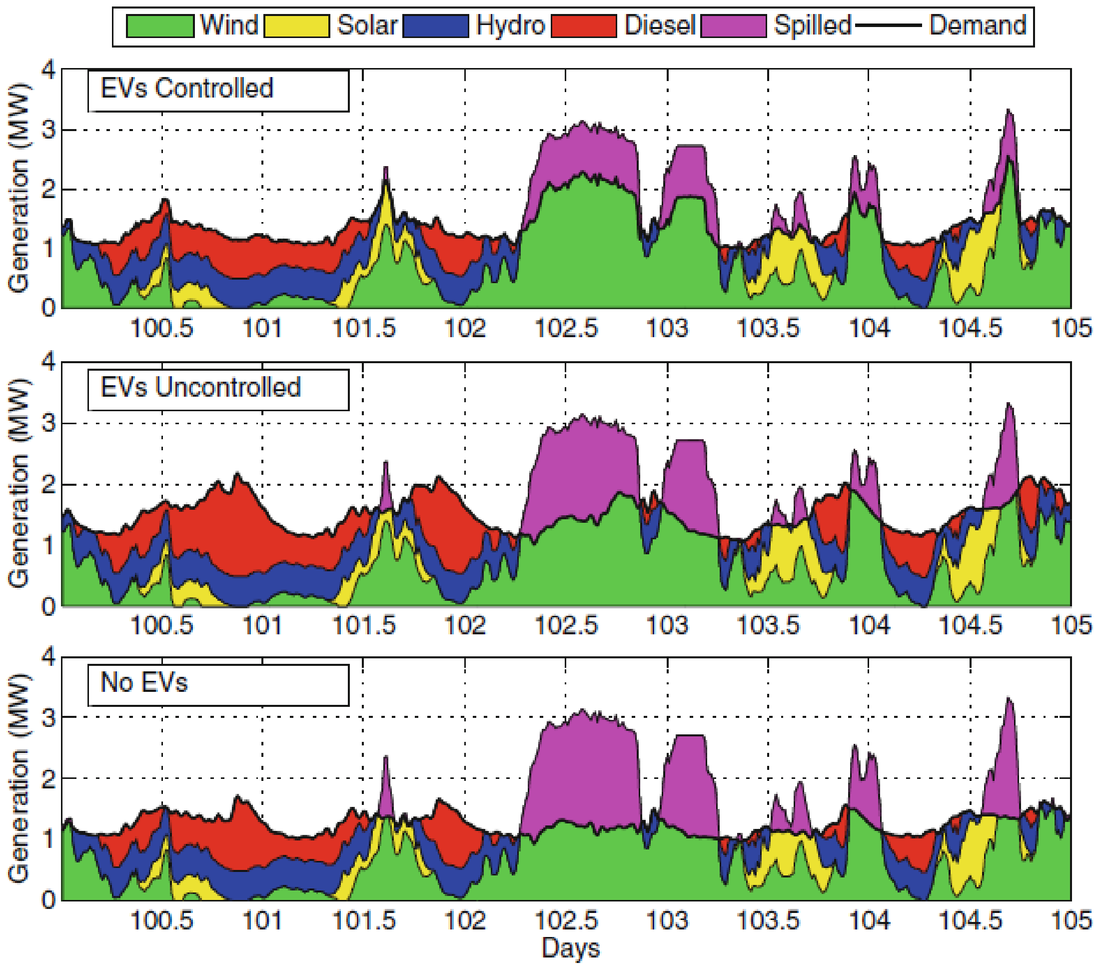


Fig. 11.10 Use of different generation types for a period in spring with 1,000 EVs in different scenarios for the case with moderate wind and solar

Major concern: Frequency regulation?

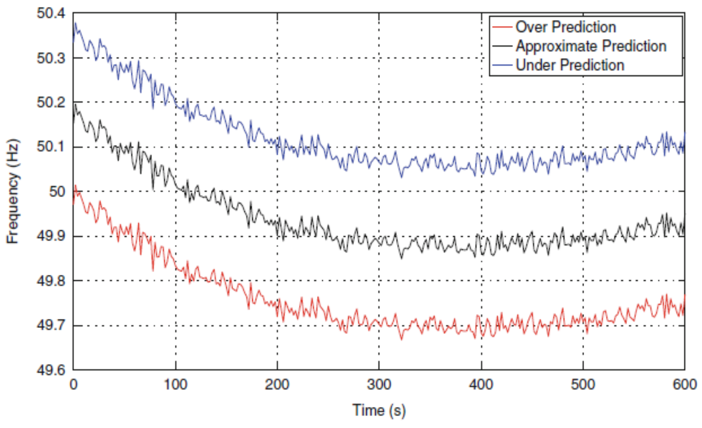
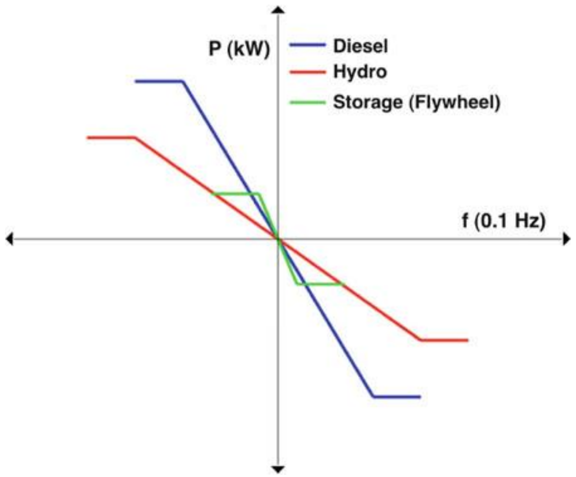


Fig. 14.3 Flores: persistent frequency deviations in the system



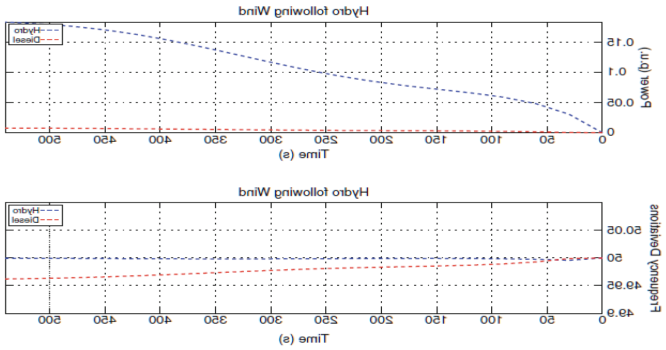


Fig. 14.9 Hydro unit balancing intra-dispatch wind variations

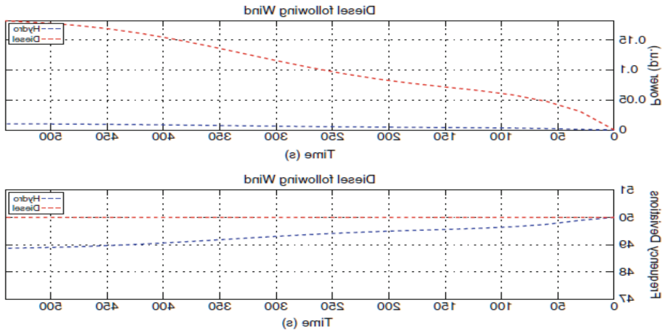


Fig. 14.10 Diesel unit balancing intra-dispatch wind variations

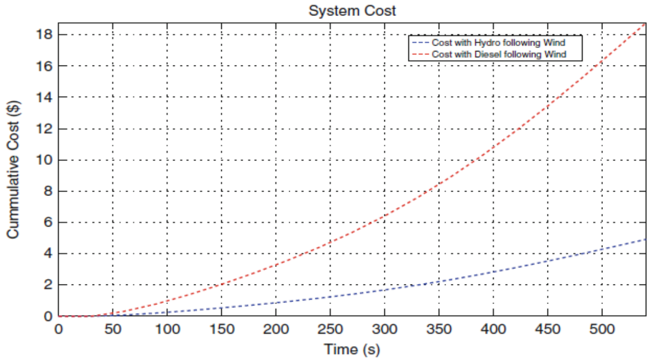
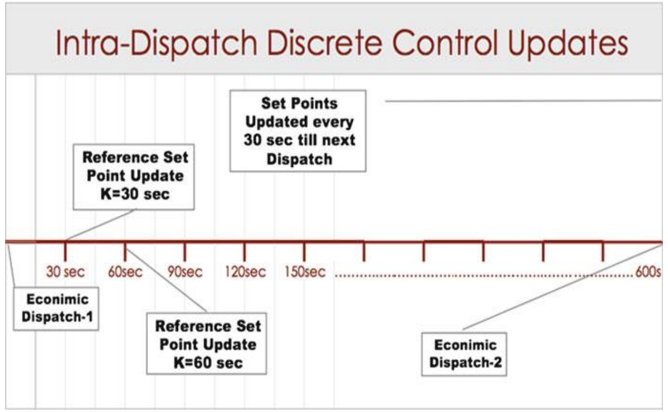


Fig. 14.14 Comparing cumulative cost over 10 min



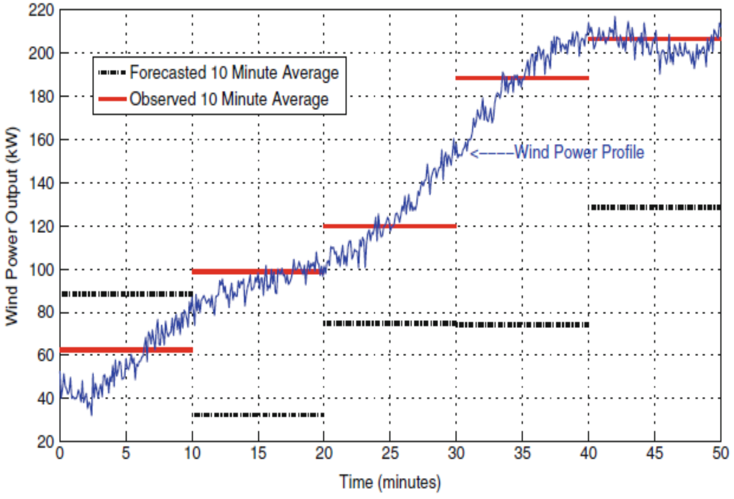


Fig. 14.1 10-Min ahead wind power forecast and actual wind power output

How to make it robust/small-signal stable?

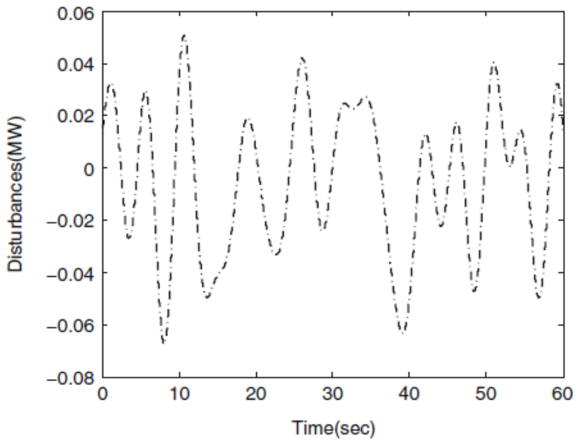


Fig. 15.7 Wind power disturbances under current penetration level

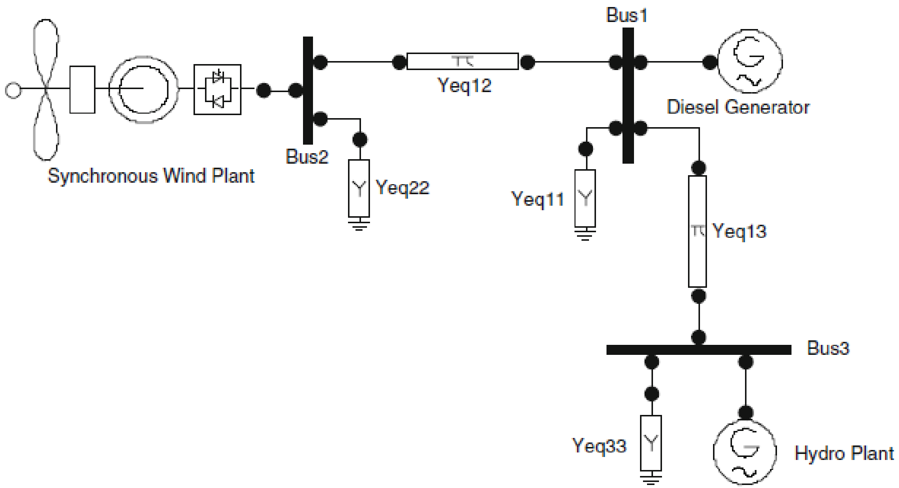


Table 15.1 Eigenvalues of the dynamic components

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	$0.07 \pm 32.73i, -126.71, -0.67 \pm 9.83, -0.18 \pm 2.87i, -0.03, -1.39, -0.46$

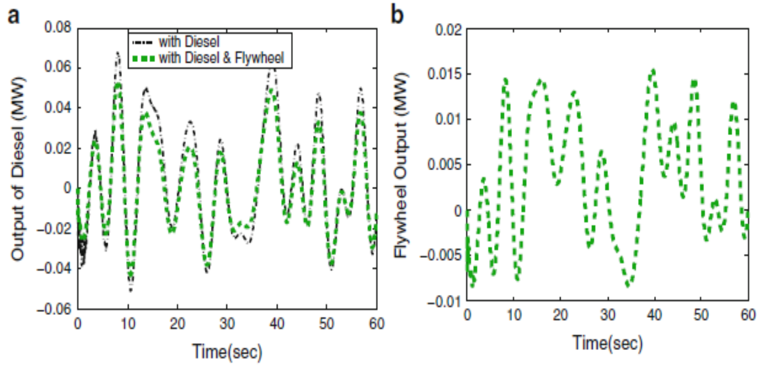


Fig. 15.9 Output of diesel and flywheel in response to frequency deviations, Case 1: system with synchronous wind generator. (a) Output of diesel generator. (b) Output of flywheel

Table 15.4 Eigenvalues of the dynamic components

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

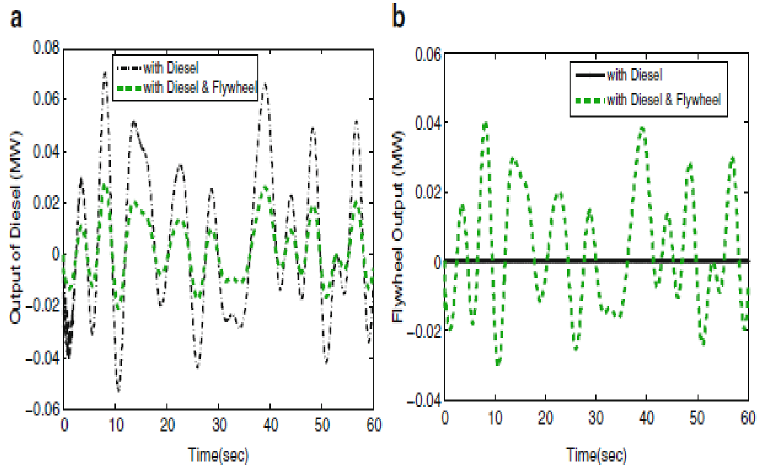
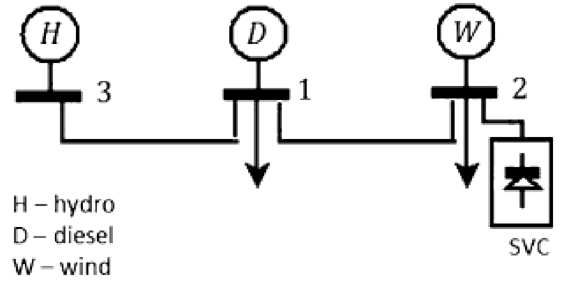


Fig. 15.11 Output of diesel and flywheel in response to frequency deviations, Case 2: system with negative load wind generator. (a) Output of diesel generator. (b) Output of flywheel

Transient stabilization in systems with wind power –SVC

Potential of Nonlinear Fast Power-Electronically-Switched Storage



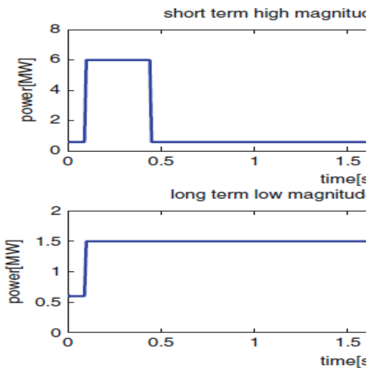


Fig. 19.2 Wind disturbances simulated in the Flores e

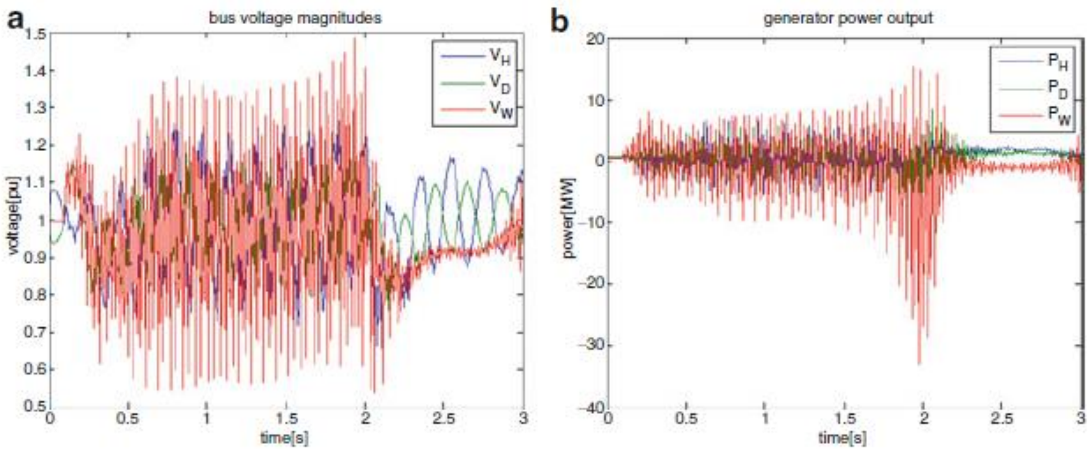


Fig. 19.14 (a) Voltage on the buses and (b) the electric power output of the generators if the system is controlled by the proposed energy-based controller

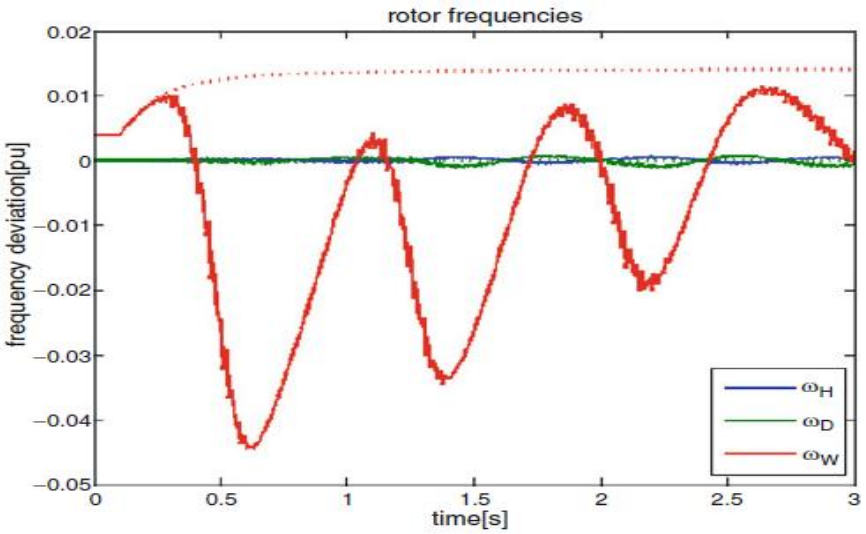


Fig. 19.16 Mechanical frequency of all generators in the system during a long-term low-magnitude wind perturbation: (a) *dashed* (without control on the SVC), (b) *solid* (with control on the SVC)

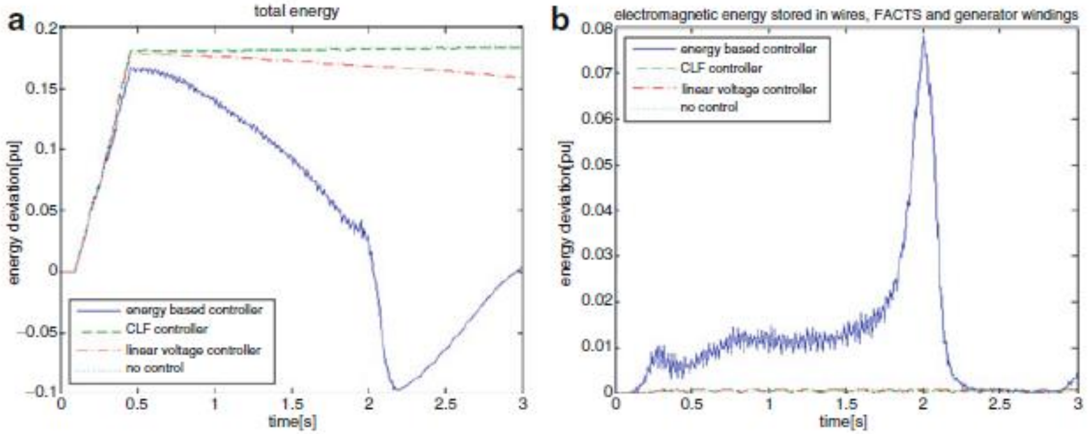
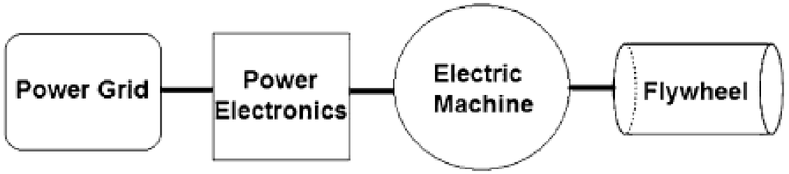


Fig. 19.15 (a) Total accumulated energy and (b) total accumulated electromagnetic energy in a system controlled by different controllers

Transient stabilization using flywheels

Concept of Sliding Mode Control Applied to a Flywheel



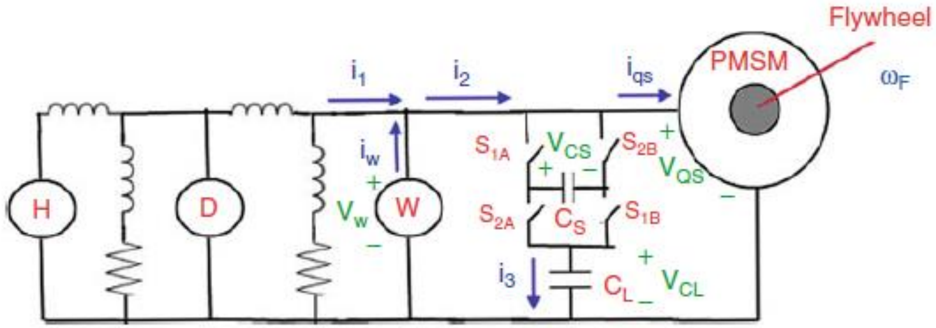


Fig. 19.34 Full diagram connecting the flywheel to Flores

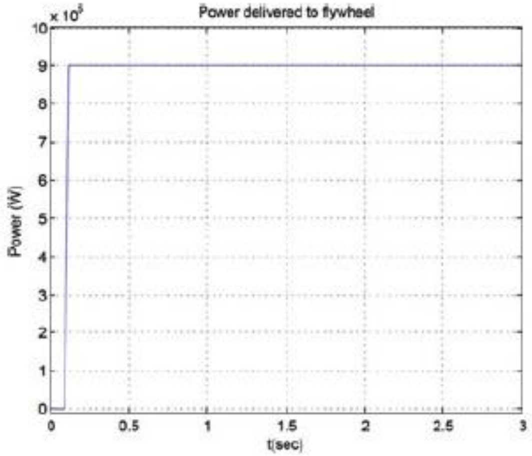


Fig. 19.32 Power delivered to the flywheel in r

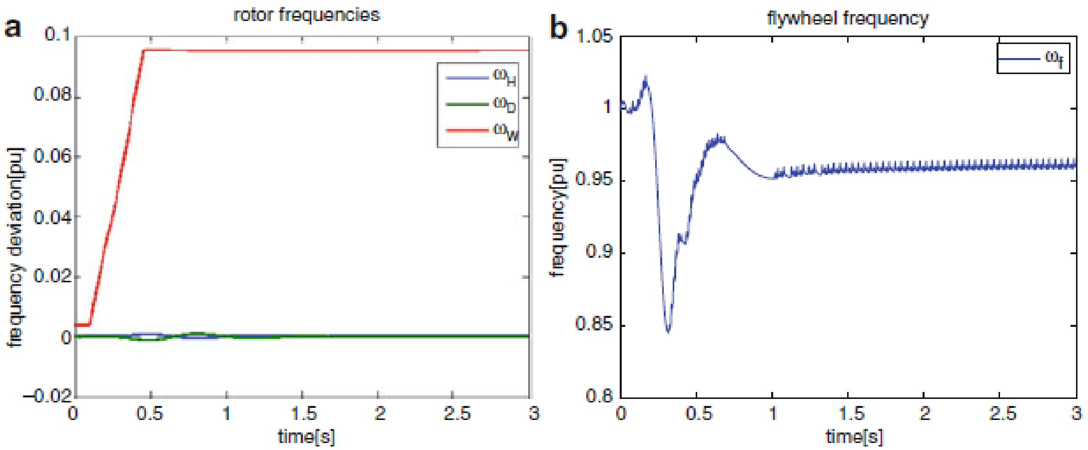
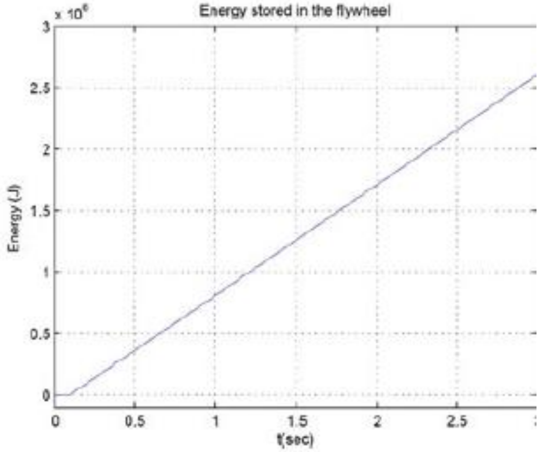


Fig. 19.35 Frequency of (a) the hydro, diesel, and wind generators, and (b) the flywheel, in the Flores system



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

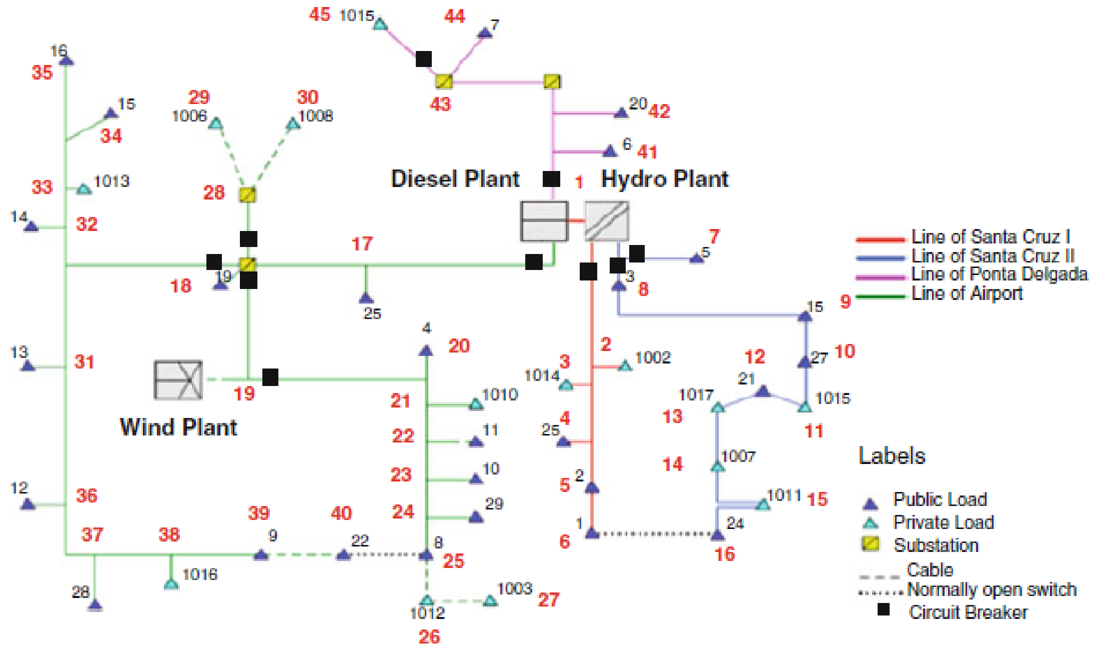


Fig. 18.1 The distribution system on the island of Flores

Toward Reconfigurable Smart Distribution Systems for Differentiated Reliability of Service

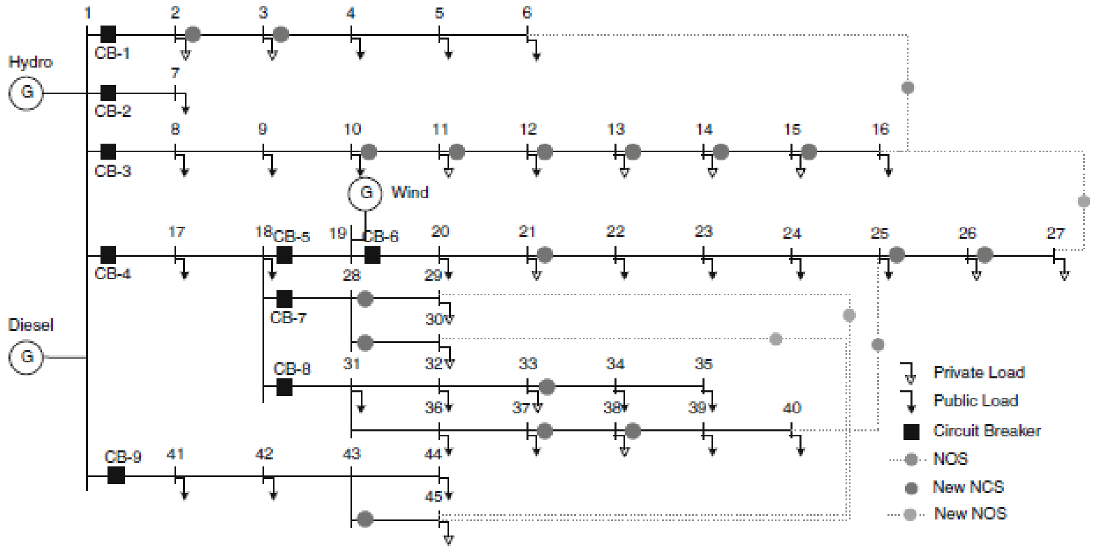
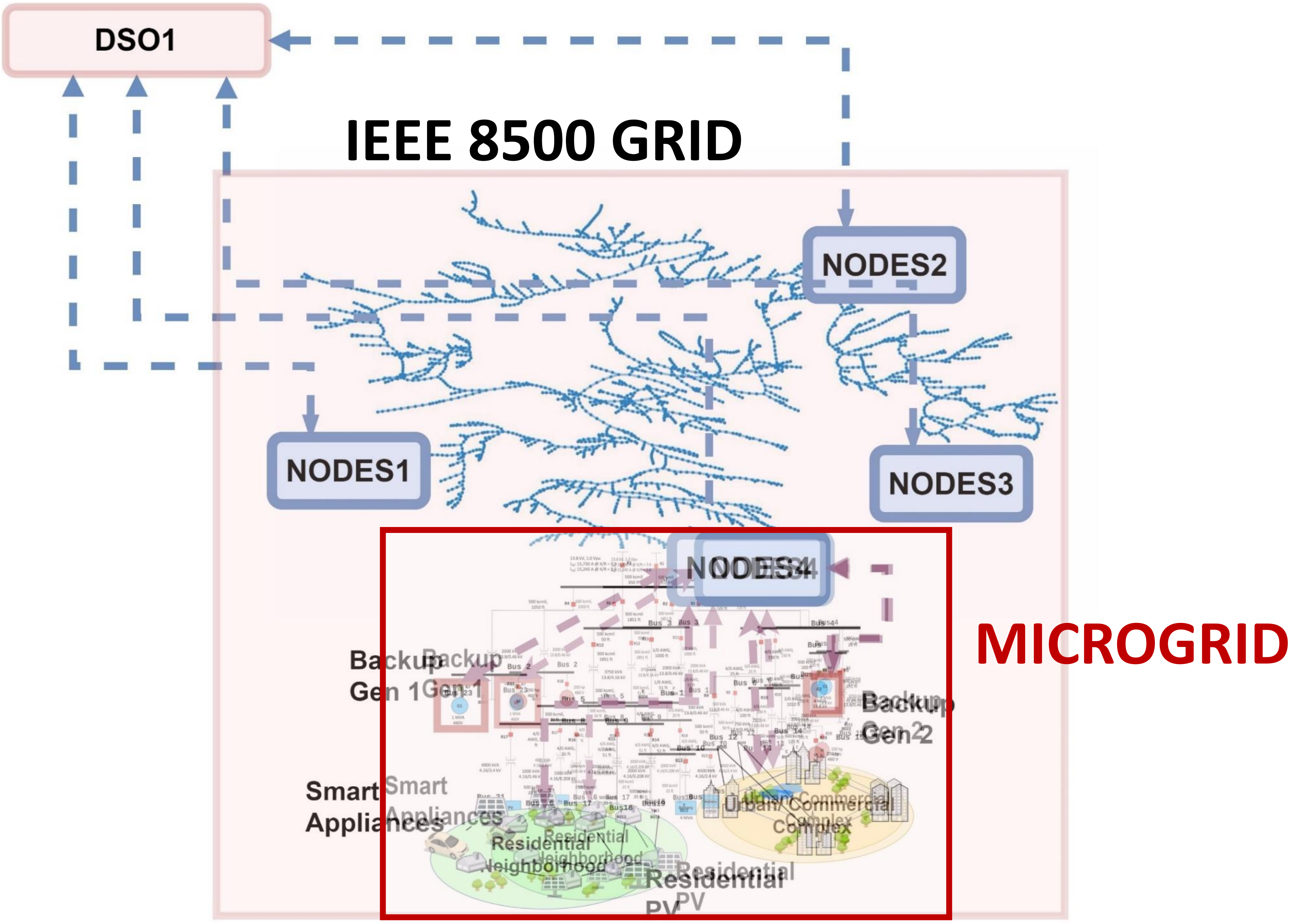


Fig. 18.4 The locations to install NCSs and NOSs

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

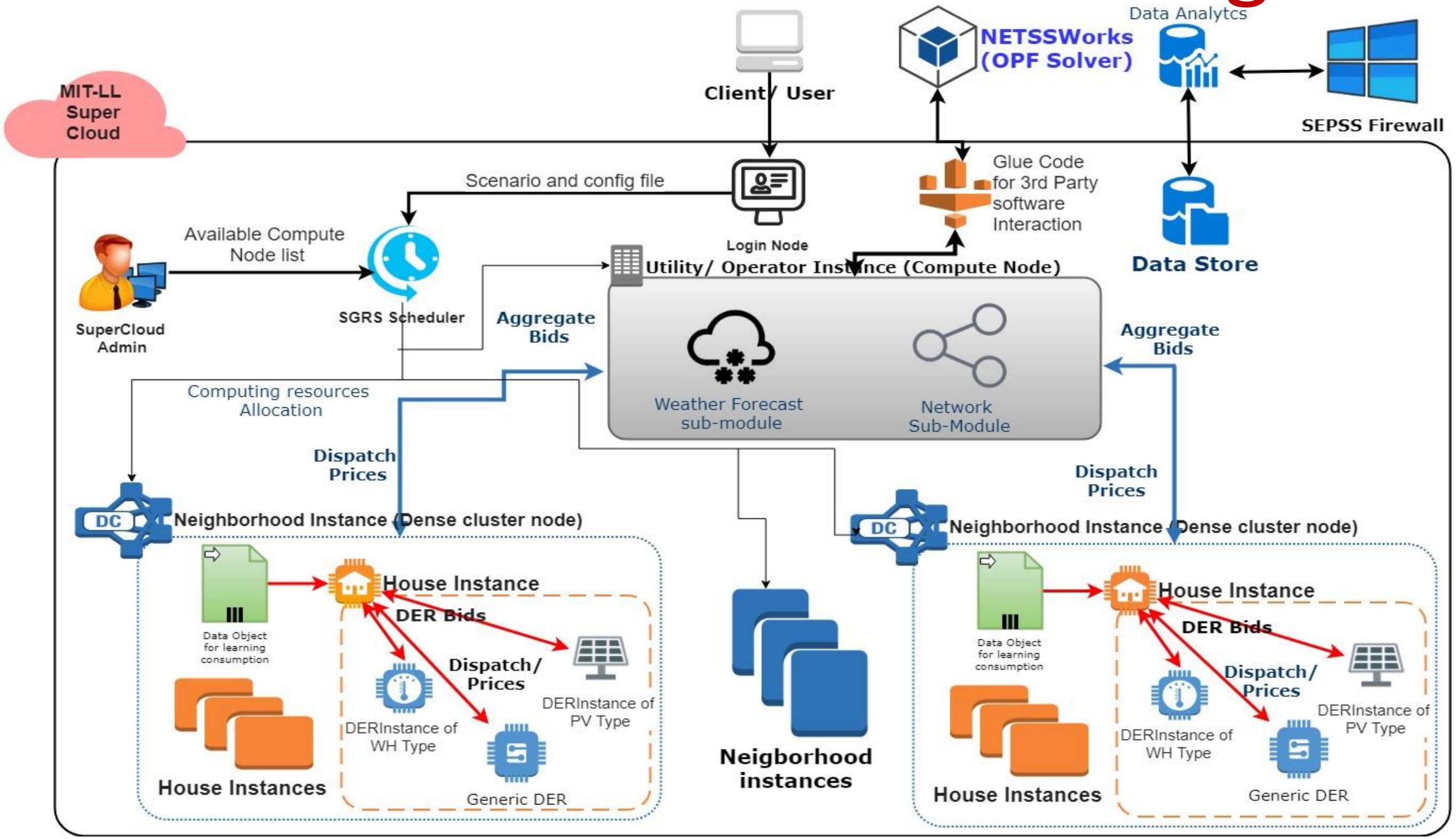

DSO1
IEEE 8500 GRID
NODES2
NODES1
NODES3
NODES4
MICROGRID
Backup Gen 1
Backup Gen 2
Smart Appliances
Residential Neighborhood
Urban Commercial Complex
Residential PV

Four TEM cases

- TEM 1 *(sunny day, fixed tariff)* – a baseline case, a combination of plug-loads and solar PVs during normal condition. PVs are negative loads.
- TEM 2 *(stormy day, fixed tariff)*---The same plug-load with sudden dip in solar.
- TEM 3 *(TOU pricing)*-- Given time-of-use (TOU) price, DERs responsive pro-active decision makers about power consumed with the objective of minimizing their energy bills.
- TEM 4 *(dynamic pricing)*- DERs and their aggregators create bids in anticipation of electricity prices, and, at the same time, they affect them (price makers).
  - TEM 4.1 *(Unlimited utility generation)*
  - TEM 4.2. *(Constrained Utility generation)*

Holmberg, David, Martin Burns, Steven Bushby, Tom McDermott, Yingying Tang, Qiuhua Huang, Annabelle Pratt et al. "NIST Transactive Energy Modeling and Simulation Challenge Phase II Final Report." NIST special publication (2019).

MIT demonstration of TEM using SEPSS*



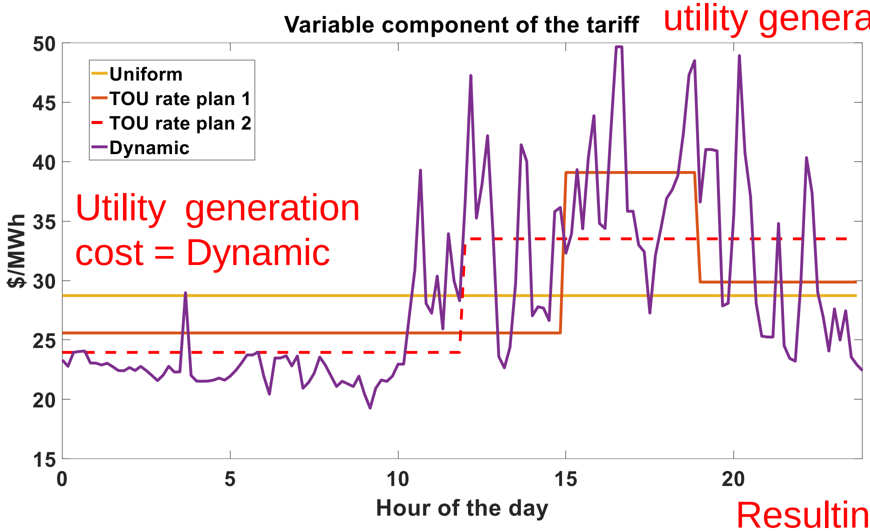
- Based on DyMonDS framework—agents with embedded decision making interacting through well-defined binding information exchange
- A scalable platform aligning embedded spatial and temporal hierarchies with the computer architecture
- Third party software (NETSSWorks) integrated to exploit its voltage optimization capability in its OPF problem
- SGRS scheduler utilized to initiate the simulation, eliminating the need for having a co-simulation master program

**Holmberg, David, Martin Burns, Steven Bushby, Tom McDermott, Yingying Tang, Qiuhua Huang, Annabelle Pratt et al. "NIST Transactive EnergyModeling and Simulation Challenge Phase II Final Report." NIST special publication (2019).*

Comparison of pricing and effect of utility generation cost

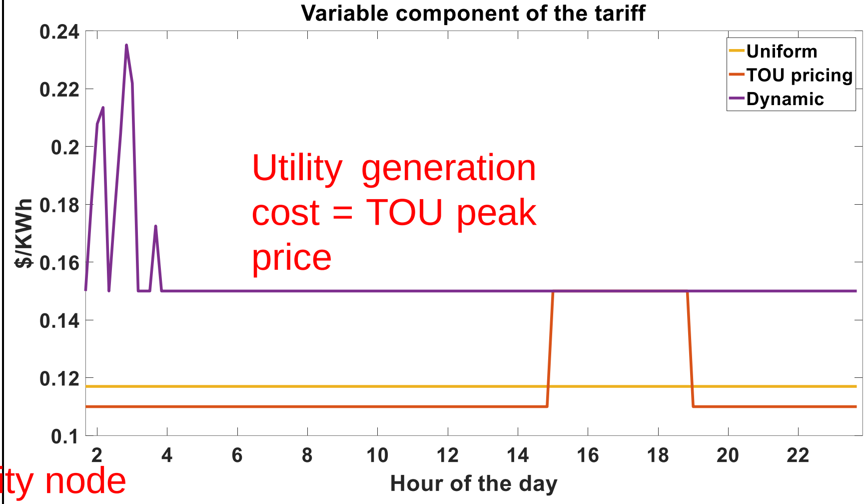
Possible tariff structure for each of the TEM cases, for assumed utility generation cost

Time-varying LMP-driven



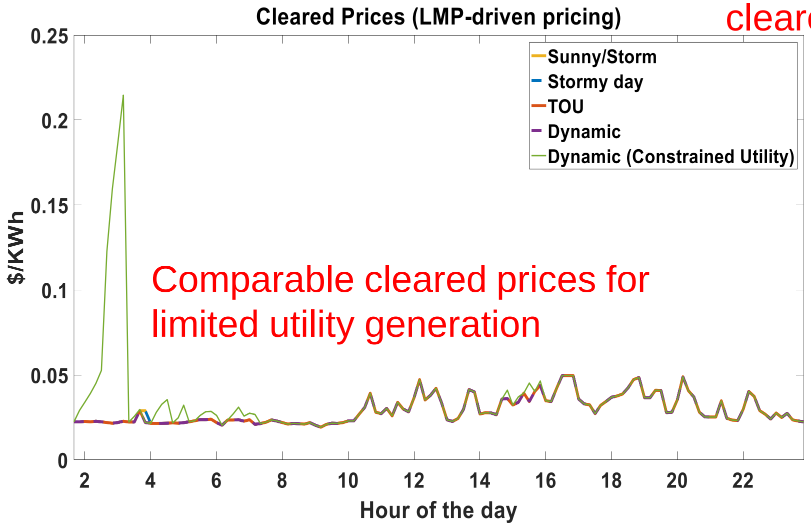
Utility generation cost = Dynamic

TOU Tariff-driven

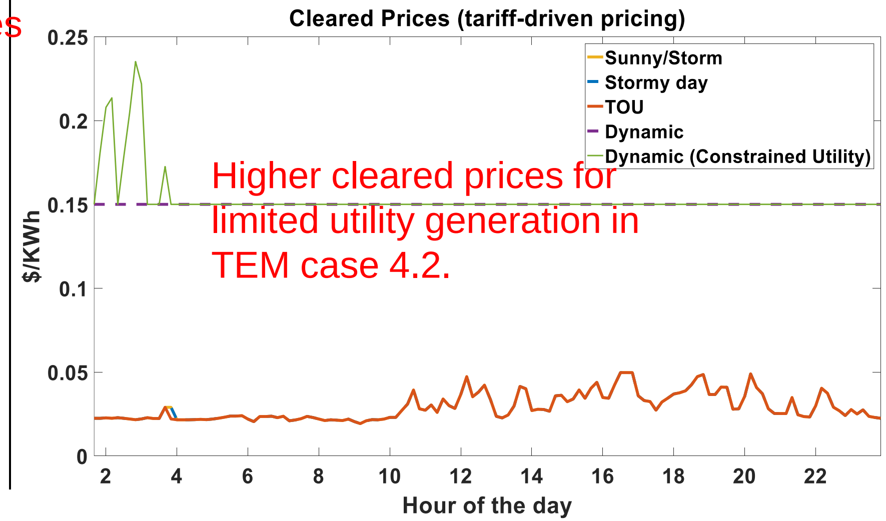


Utility generation cost = TOU peak price

Resulting utility node cleared prices



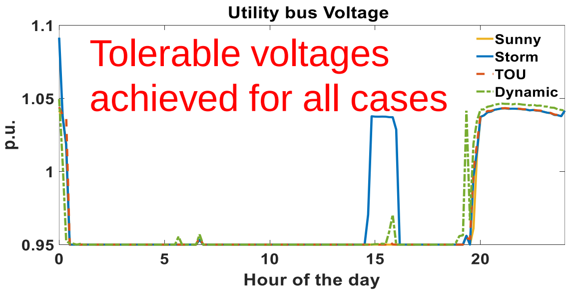
Comparable cleared prices for limited utility generation

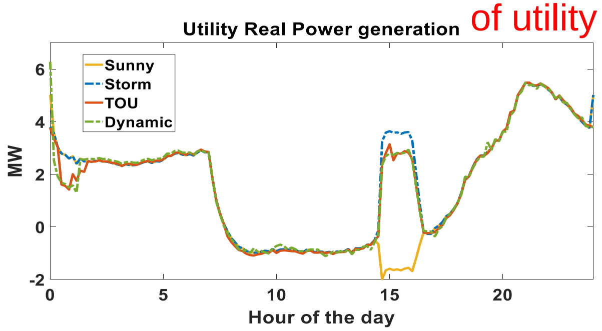


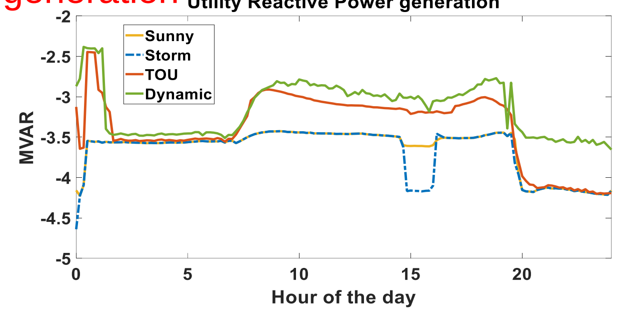
Higher cleared prices for limited utility generation in TEM case 4.2.

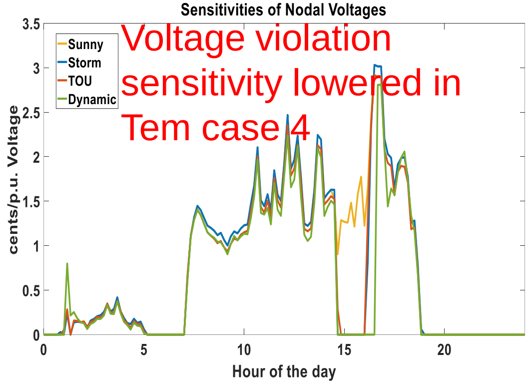
Impact of TEM on utility—technical and economic metrics

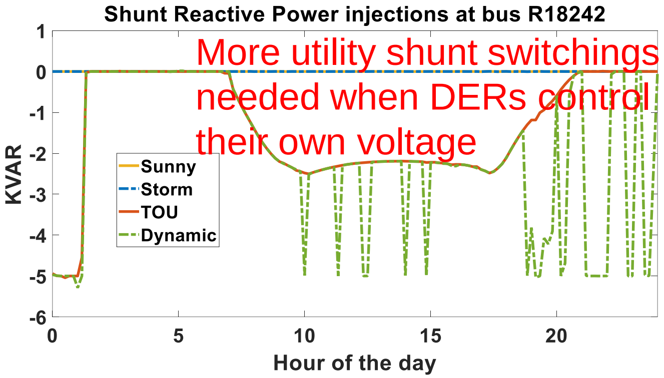
Effect of MPC resulting in lesser requirement of ramping reserves of utility generation

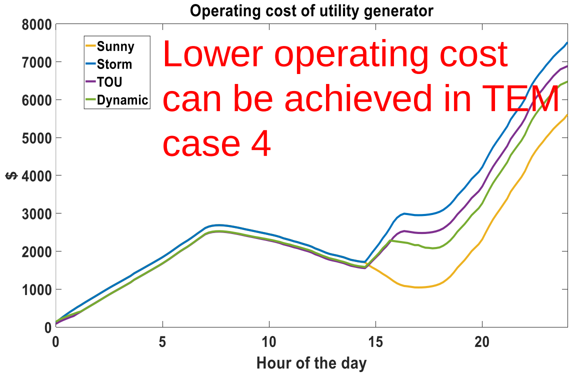








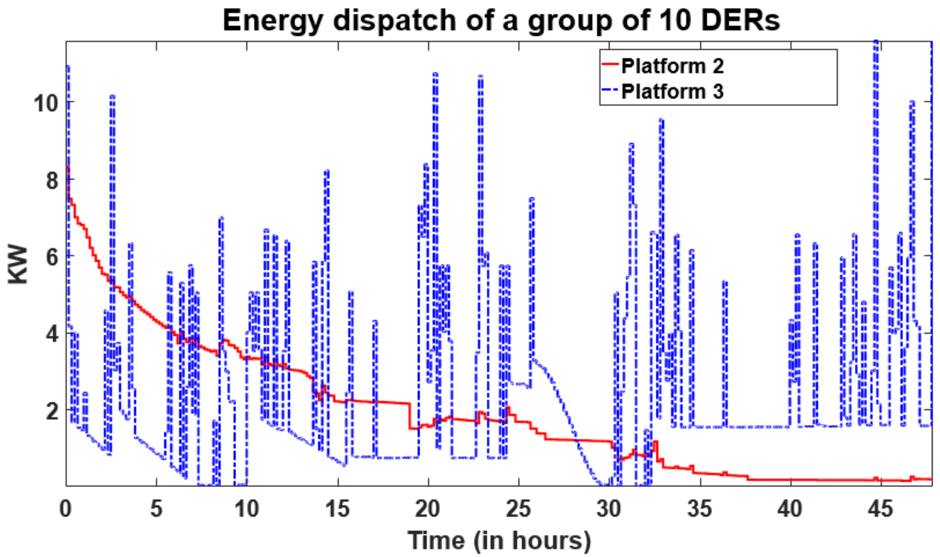


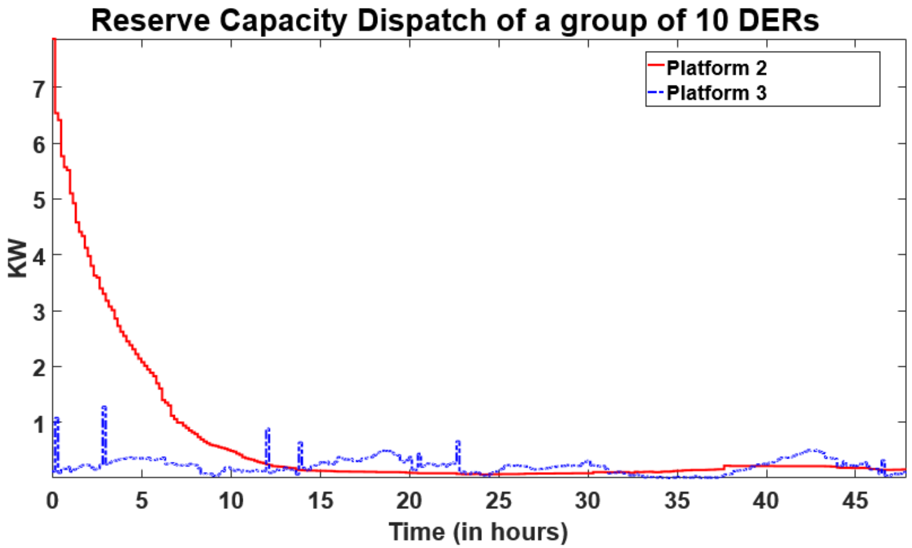


OBSERVATIONS –utility COULD PLAY A MAJOR ENABLING ROLE; BASIS FOR PEAK LOAD PRICING AND PERFORMANCE BASED REGULATION

NEED FOR ASSESSING AND IMPROVING HOSTING CAPACITY AT VALUE

Performance with/wo economic signals





More granular decision making at prosumer level results in possibly larger reserve capacity dispatch and more flexibility in energy adjustment schedules of DERs

Technical, business and societal challenges and opportunities

5.3.7. Roles and performance metrics of different TEM participants

Shown in Table MIT-1 is an illustration of roles and performance metrics of TEM participants for the four TEC cases.

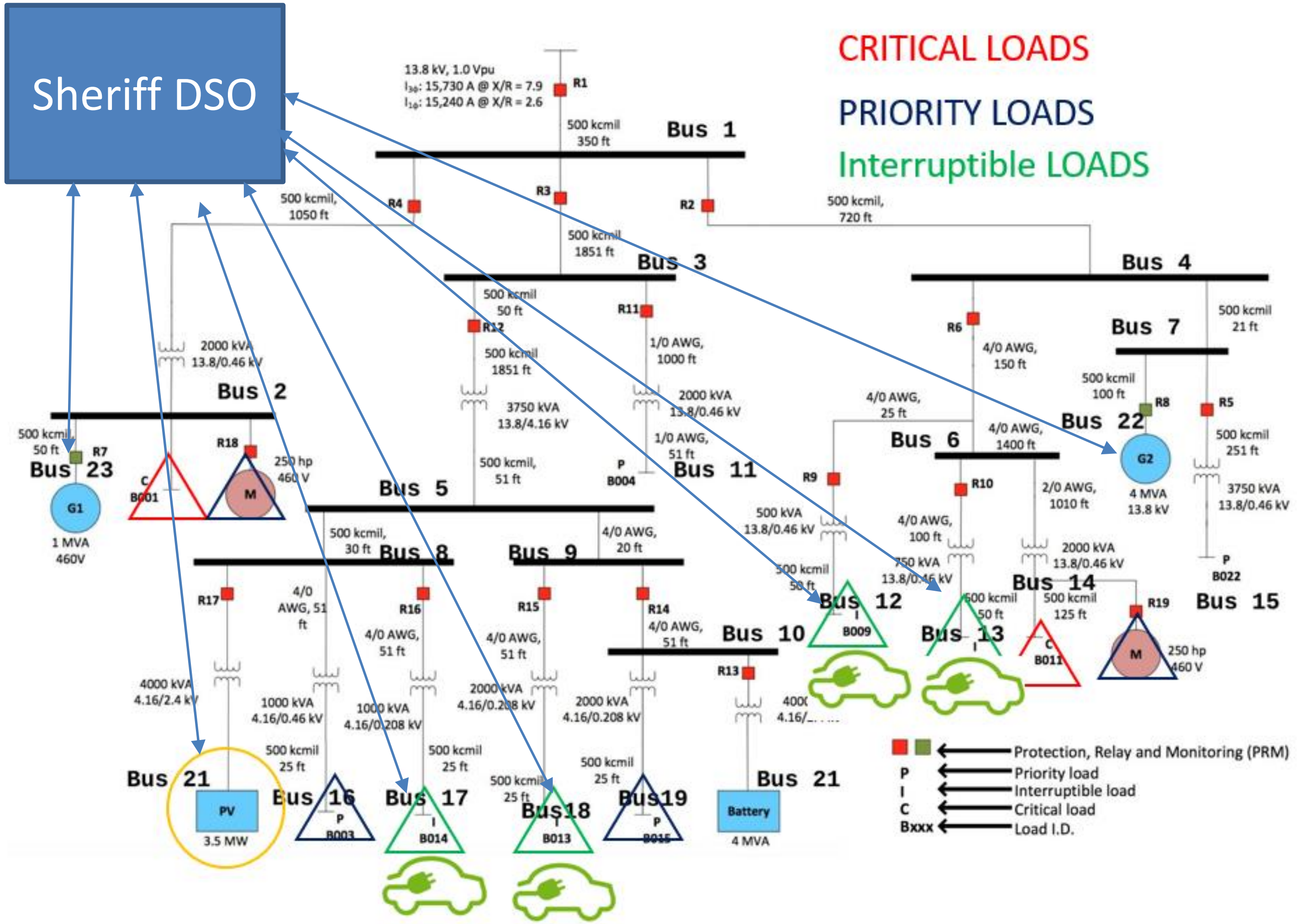
Table MIT-1 Roles and Performance metrics in TEC cases

Case	End-users		Distribution Grid		Market		Notes
	Role	Sub-Objective	Role	Sub-Objective	Role	Sub- Objective	
1. normal sunny day	Passive	utilize solar power	Critical, including possible reverse flows	feasible power delivery; ANSI C84.1	minimal	Economic efficiency	Operating problems time-varying. Baseline case.
2. Storm in the middle of Case 1	Passive	have power during both normal conditions and during storm	Role of distribution grid--critical	Sub-objective – feasible power delivery; ANSI C84.1	minimal	Economic efficiency	Potential problems during storm
3. Time-of-Use	decide on power to use	Minimize energy bill; maximize local efficiency; ensure comfort; support voltage or not.	less critical; end users could support their voltage; participate in delivery	feasible, physically efficient delivery; if supporting voltage, build smart infrastructure	minimal	Economic efficiency	Could be conflicting sub-objectives; Need for voltage support protocol
4. dynamic electricity pricing	decide on bidding	Minimize energy bill; maximize local efficiency; ensure comfort; support voltage or not.	less critical; end users could support their voltage; participate in delivery; MUST GIVE SIGNAL TO MARKET	feasible, physically efficient delivery AT VALUE; if supporting voltage, build smart infra-structure; GET PAID FOR THIS	Critical; create dynamic prices which reflect not only real power but also VOLTAGE	Efficient market clearing mechanism by considering bids at value from both end users and grid	Potentially win-win fair case

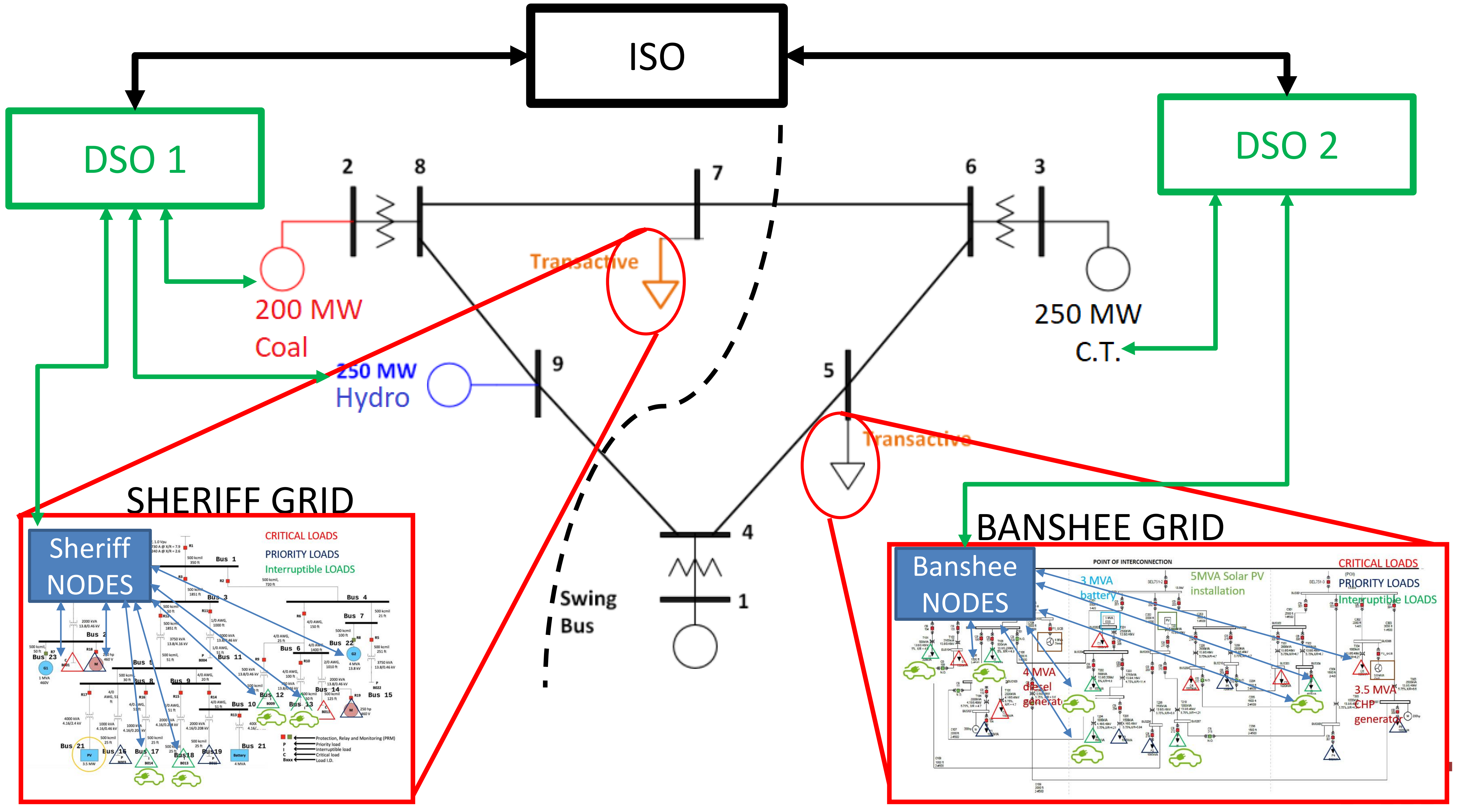
System enhancements needed—hidden traps

- ***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*

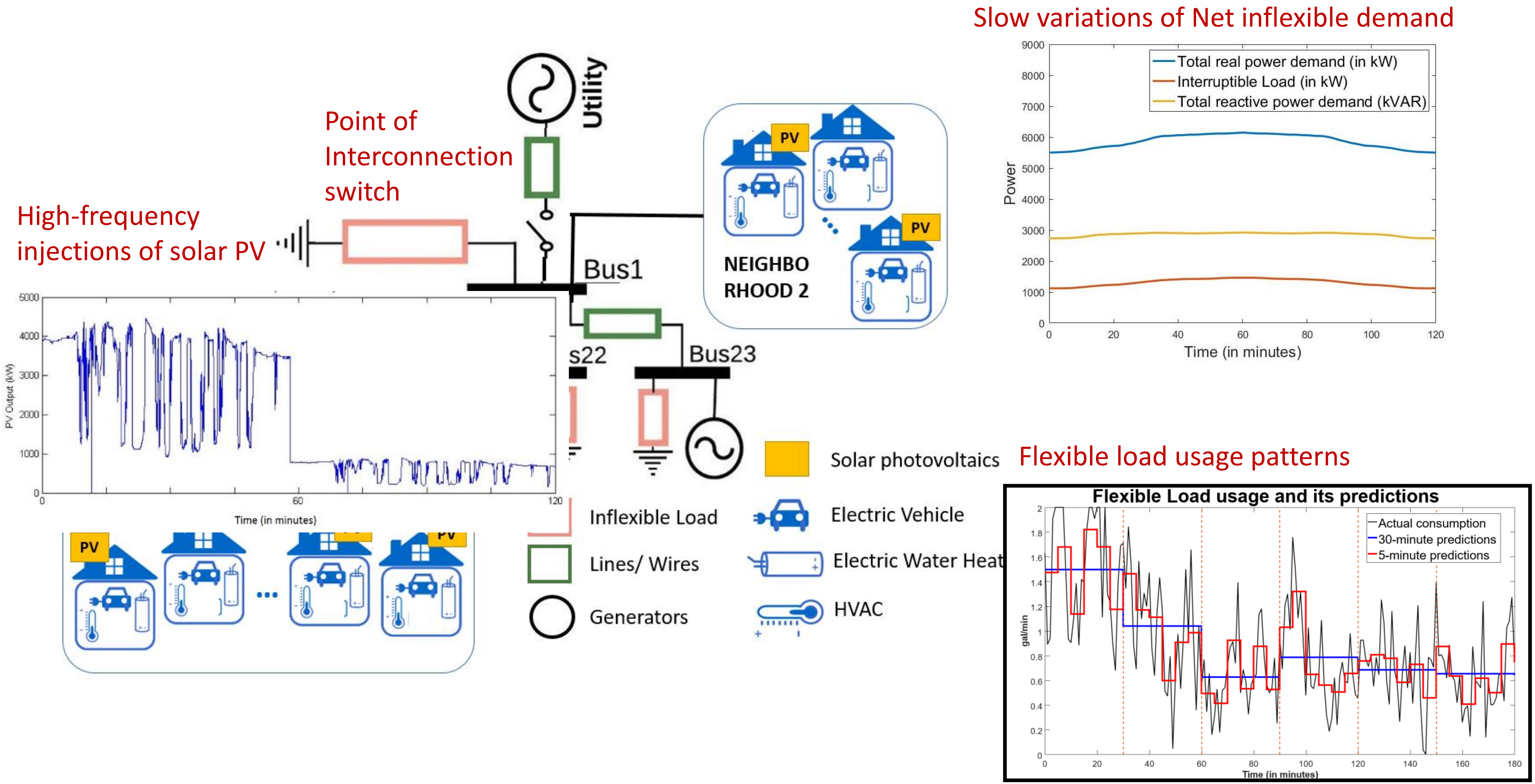
Coordinating increased penetration of renewables and demand response



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.


ISO
DSO 1
DSO 2
2
8
7
6
3
200 MW
Coal
250 MW
Hydro
9
Transactive
250 MW
C.T.
5
Transactive
4
1
Swing
Bus
SHERIFF GRID
Sheriff
NODES
CRITICAL LOADS
PRIORITY LOADS
Interruptible LOADS
BANSHEE GRID
Banshee
NODES
POINT OF INTERCONNECTION
3 MVA
battery
5MVA Solar PV
installation
CRITICAL LOADS
PRIORITY LOADS
Interruptible LOADS
4 MVA
diesel
3.5 MVA
CHP
generator

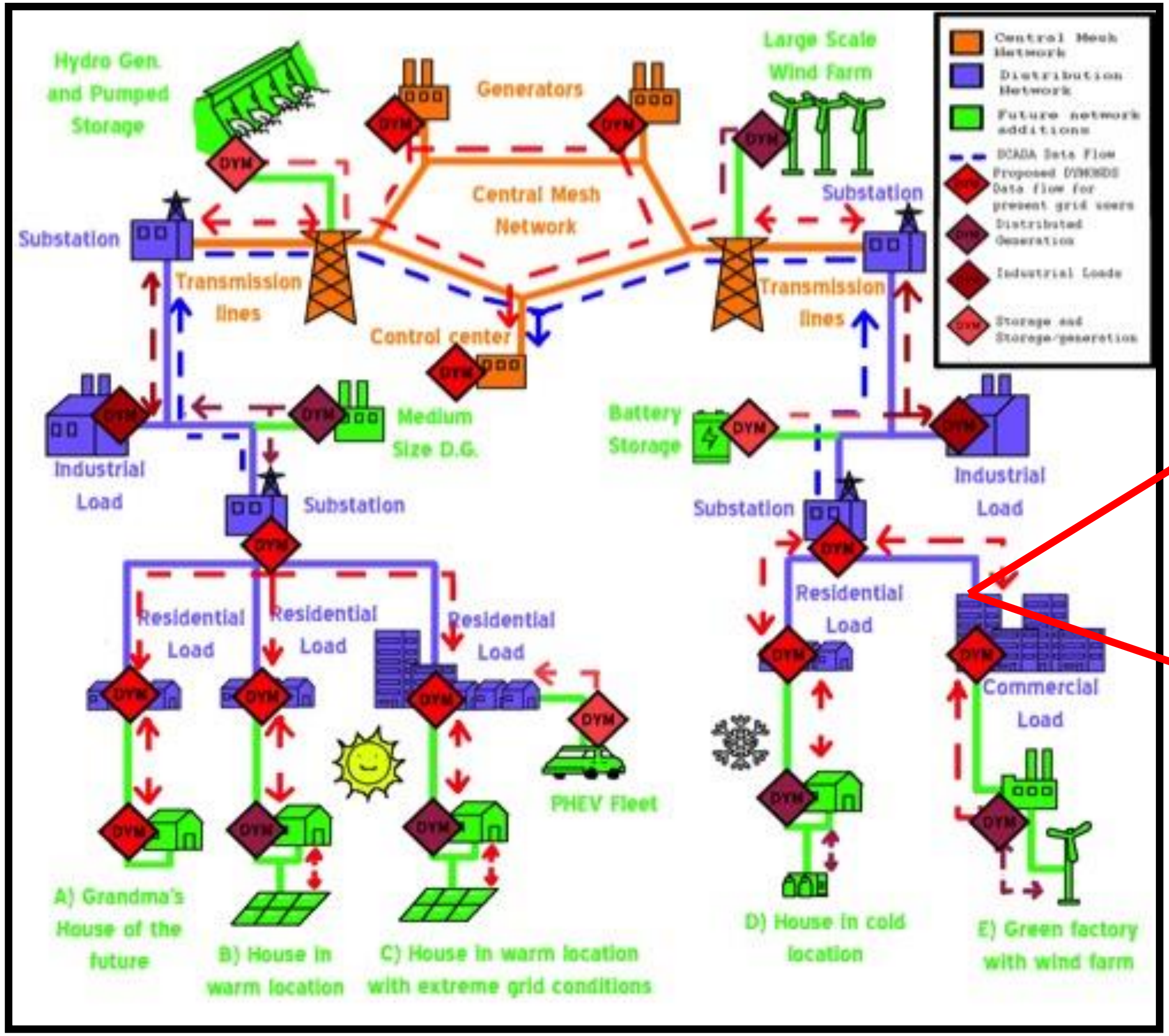
Typical feeder and its inputs

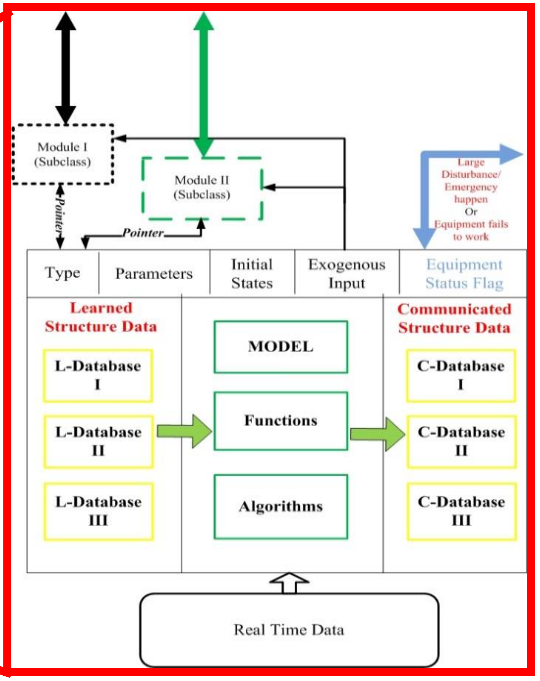


Emerging system; needs for enhancing SCADA

- Multi-layered operations/ownerships
- Need to integrate renewables; DERs; demand side
- No end-to-end communications for cooperative electricity service
  - Bulk power system (BPS) with SCADA; the rest has no information exchange for proactive participation
- Need minimal, carefully designed communication platform that builds on the existing BPS SCADA

General DyMonDS

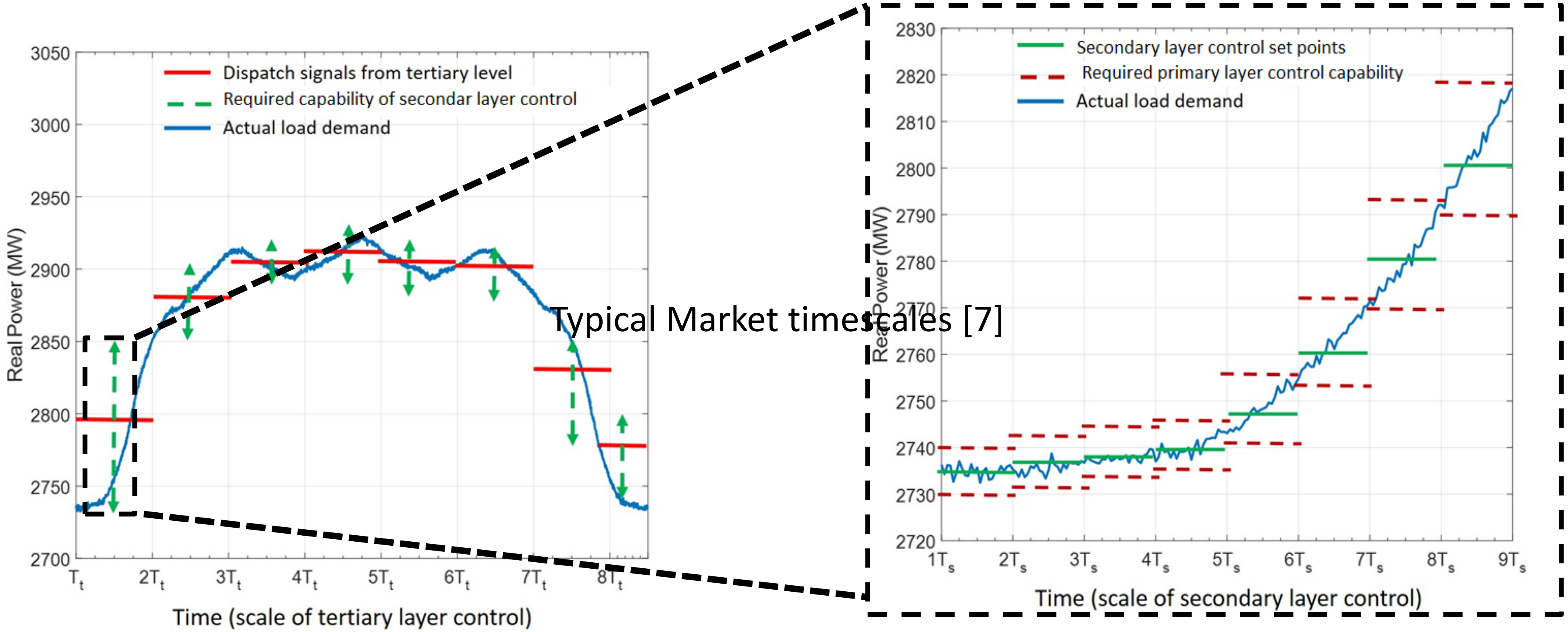




Local DyMonDS module

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

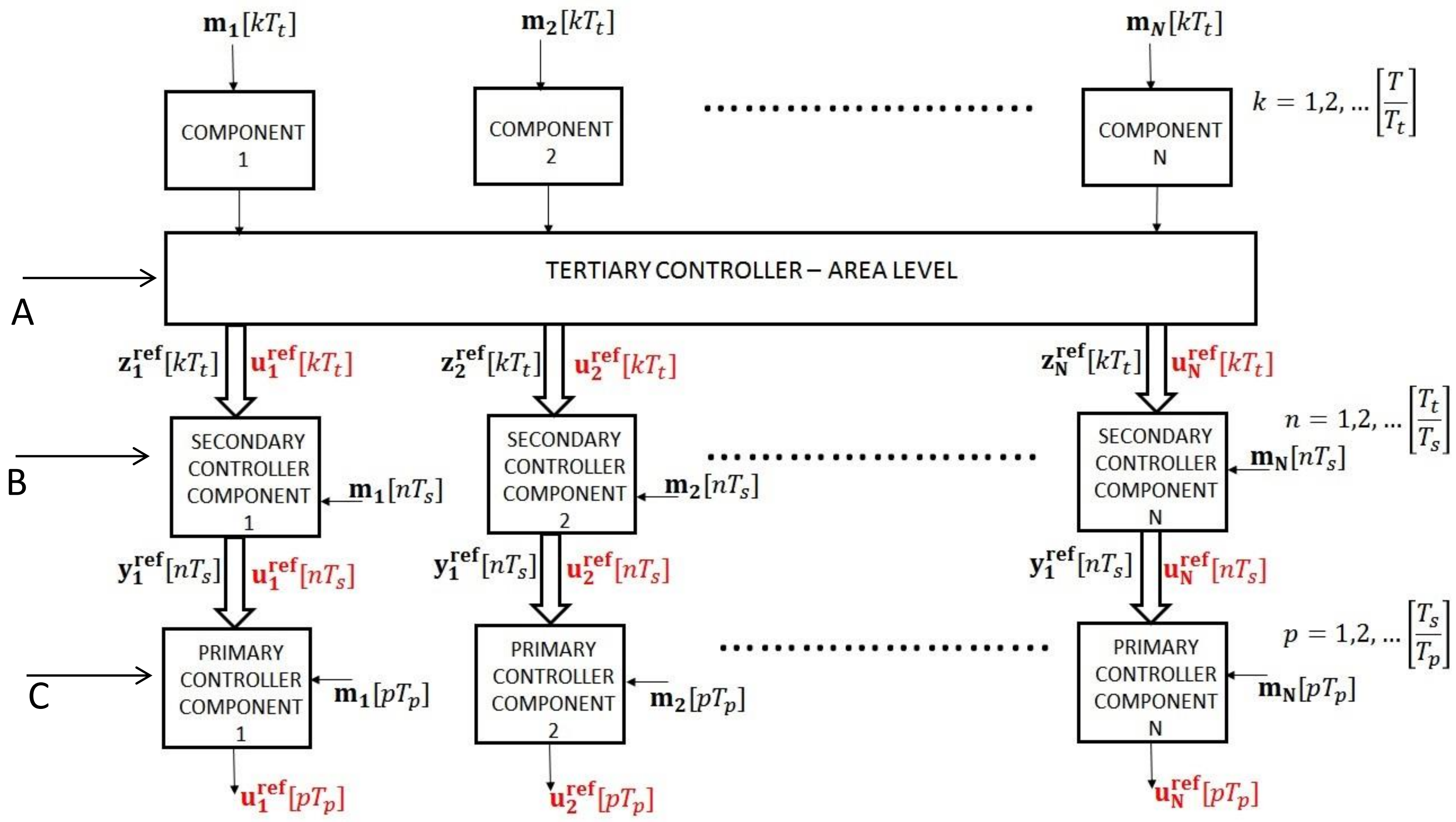
Temporal Decomposition of inflexible demand for market operations



TAKE-AWAY 1: MUST UNDERSTAND/MANAGE DYNAMICS OVER SEVERAL TIME HORIZONS..

Ilic, M.D., 2016. Toward a unified modeling and control for sustainable and resilient electric energy systems. Foundations and Trends® in Electric Energy Systems, 1(1-2), pp.1-141.

Hiearchical control in microgrids



Foundations and Trends in Electric Energy Systems, Vol. 1, No. 1 (2016) 1–141,c 2016 Marija D. Ilic ́ DOI: 10.1561/3100000002

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. Service can 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

**Ilic, Marija, Carvalho, Pedro, Lessard, Donald, `` Minimal Coordination of Dynamic Reserves for Flexible Operations at Value: The Case of Azores Islands”, IEEE PES GM 2021, Paper forum.*

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

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

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

Potential of using AC Optimal Power Flow (AC OPF) for identifying grid operation bottlenecks*

Challenge problem: MICROGRID CONTROL	Actions required – based on typical ED microgrid controller	Actions required –based on advanced microgrid controller	QUANTIFABLE DIFFERENCES
Case S1 (Sheriff, high load, low PV power)	No steady state solution within limits	PV must produce reactive power Need to add shunts at critical buses	Can operate without load shedding
Case B1 (Banshee, interconnected, all NoS)	No steady state solution within limits	Battery serve in grid forming mode; optimized taps on critical transformers	Can operate without load shedding
Case B2 (Banshee, islanded all NcS)	No steady state solution within limits	Both PV and battery serve in grid forming mode; key transformer taps optimized	Can operate without load shedding

**Ilic, Marija, Potential of Advanced Microgrid Control: Cases of Sheriff and Banshee, EESG@MIT white paper WP-2017-1.*

Question 2:Enabling feasible and stable modeling and control?

Possible way forward: Multi-layered functional specifications-energy dynamics

- 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

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

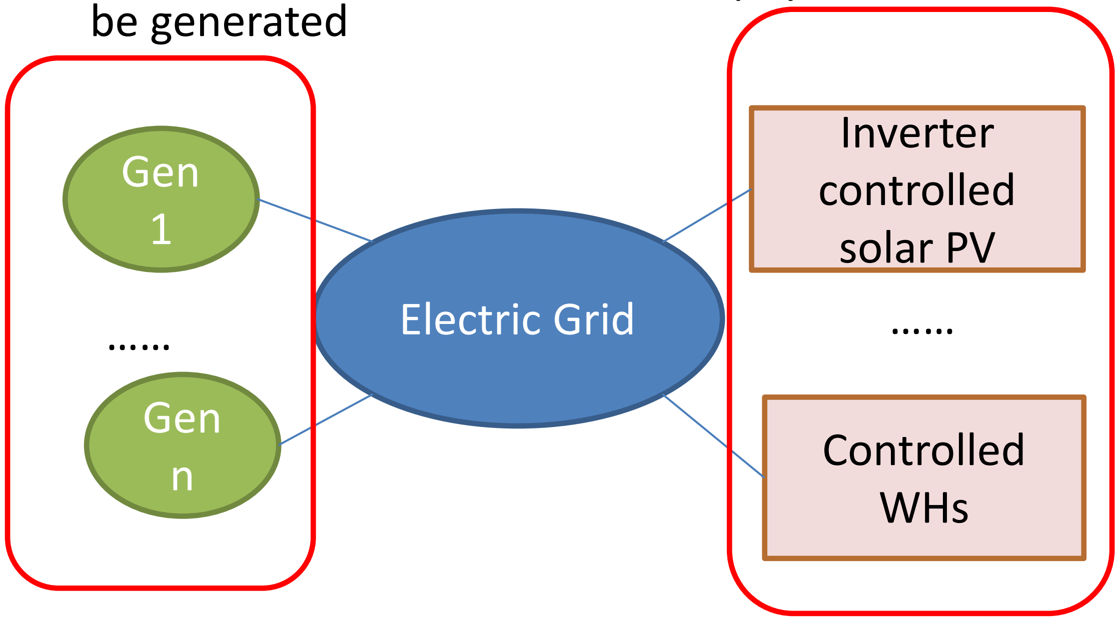
  -make the case for physics-based processing underlying ``smarts" design

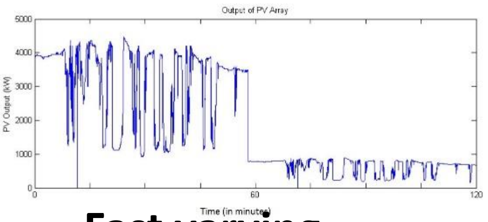
Miao, X., Ilić, M., Smith, C., Overlin, M. and Wiechens, R., 2020, October. Toward Distributed Control for Reconfigurable Robust Microgrids. In *2020 IEEE Energy Conversion Congress and Exposition (ECCE)* (pp. 4634-4641). IEEE.
https://patents.justia.com/patent/10656609, **Patent number:** 10656609, April 2018.
Miao, Xia, and Marija D. Ilić. "High Quality of Service in Future Electrical Energy Systems: A New Time-Domain Approach." *IEEE Transactions on Sustainable Energy* 12, no. 2 (2020): 1196-1205.

Basic ideas underlying the energy-based dynamical models

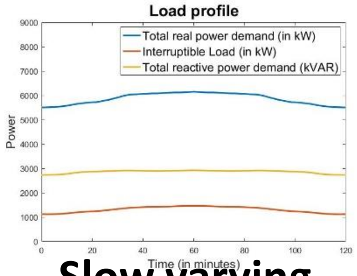
Inertia used as a proxy to rates at which energy can be generated

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) – based approximated system analysis no longer are valid

Basis for energy as a state variable

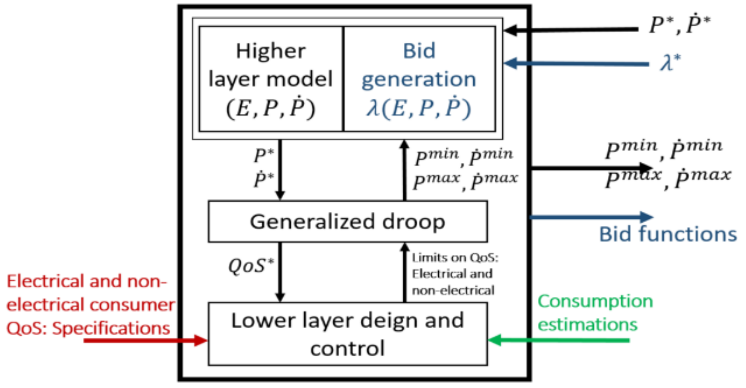
Power conservation laws always hold at the interfaces of components and/or sub-systems.

Basis for real power as an interface variable

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.

Basis for reactive power as an interface variable

Unified multi-layered functional specifications



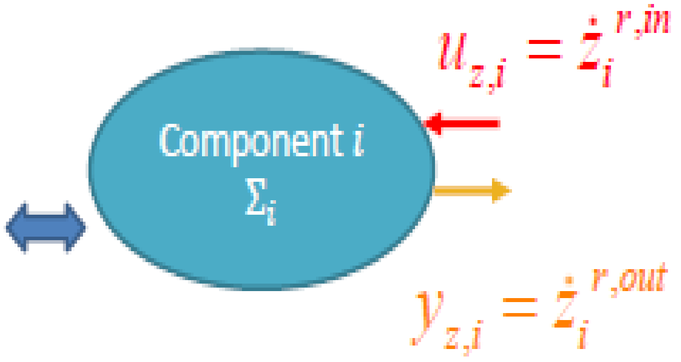
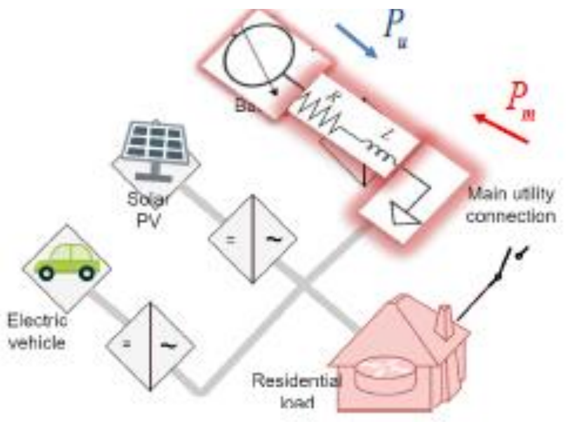


Fig 3: Energy-power model of a general component



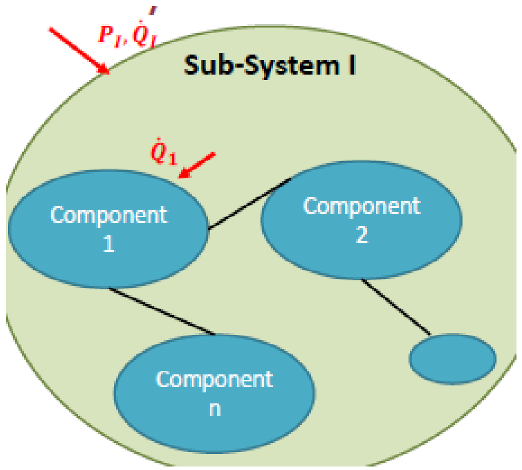


Fig 4: Energy-power model of an interconnected microgrid

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.

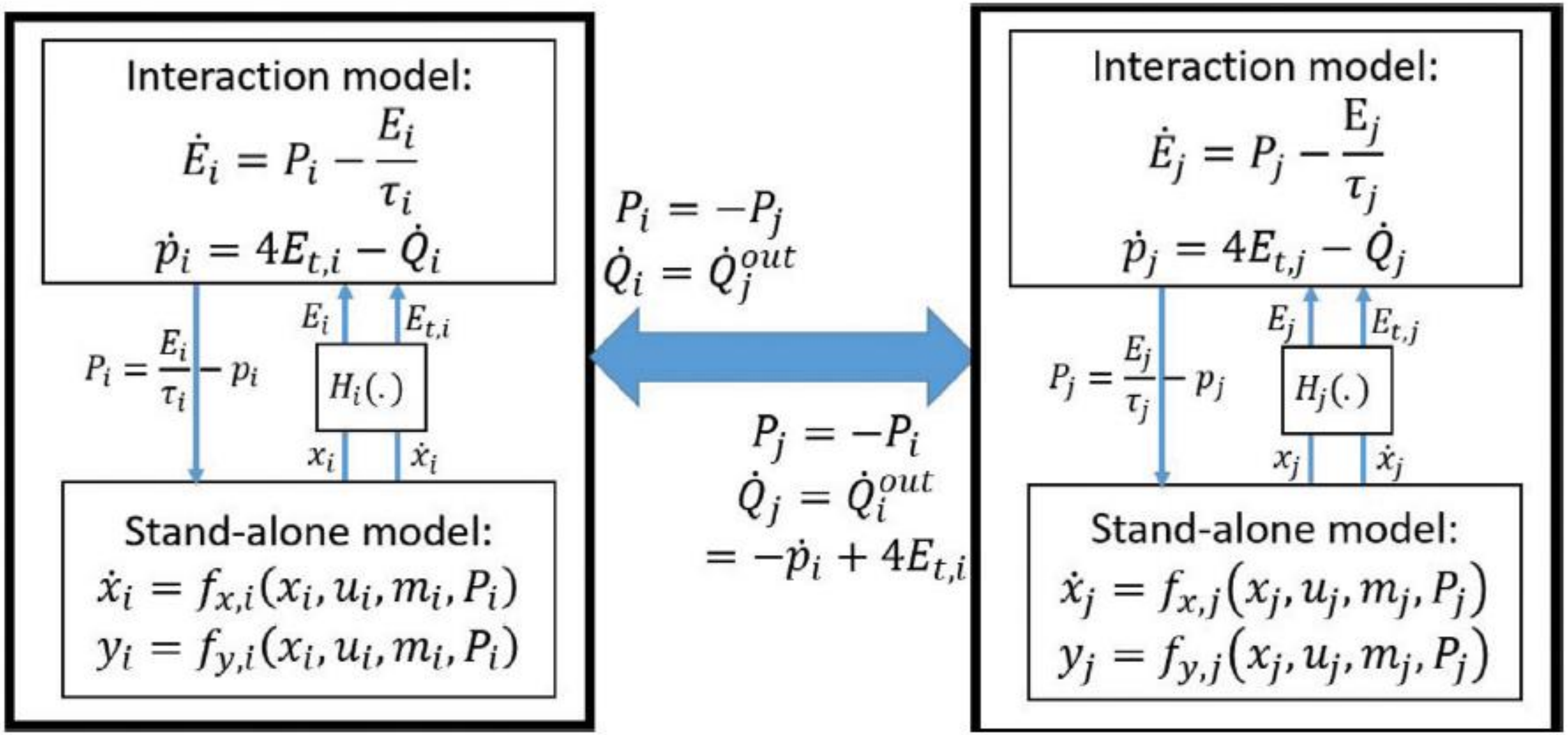
Ilic, Marija D., and Rupamathi Jaddivada. "Fundamental modeling and conditions for realizable and efficient energy systems." *2018 IEEE conference on decision and control (CDC).* IEEE, 2018.

Provable IT--enabled prosumer participation? [9,10]

Understood by engineers and economists !

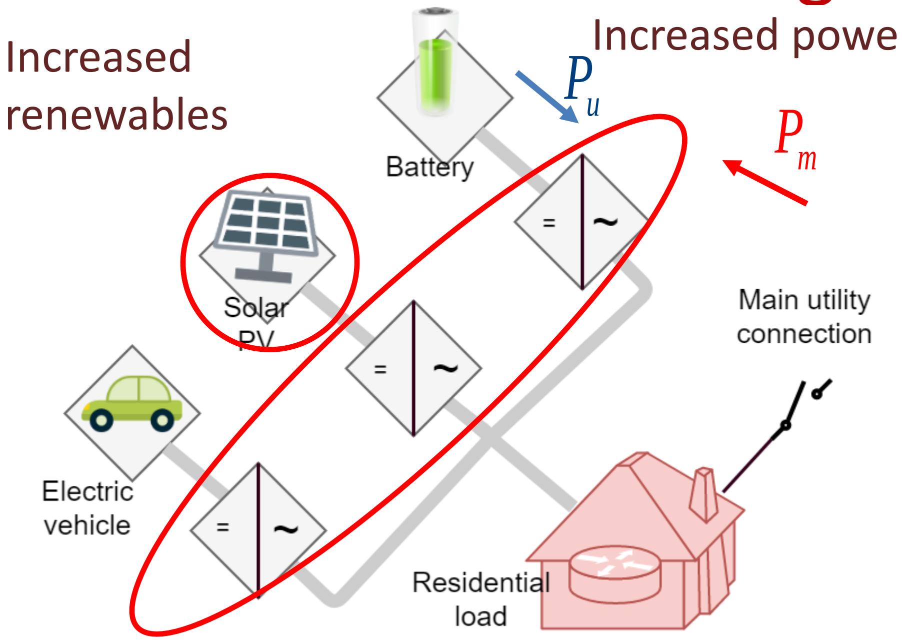
- Common energy-based modeling of heterogeneous prosumers
- Unified specifications
  - For operations: $(E, P, \dot{P})_{T_\alpha}$ triplet for operation
  - For markets: Bids for each of the triplet $\lambda(E, P, \dot{P})_{T_\alpha}$
- Modeling and control for implementing prosumer specifications
- Signals for markets and operations aligned!

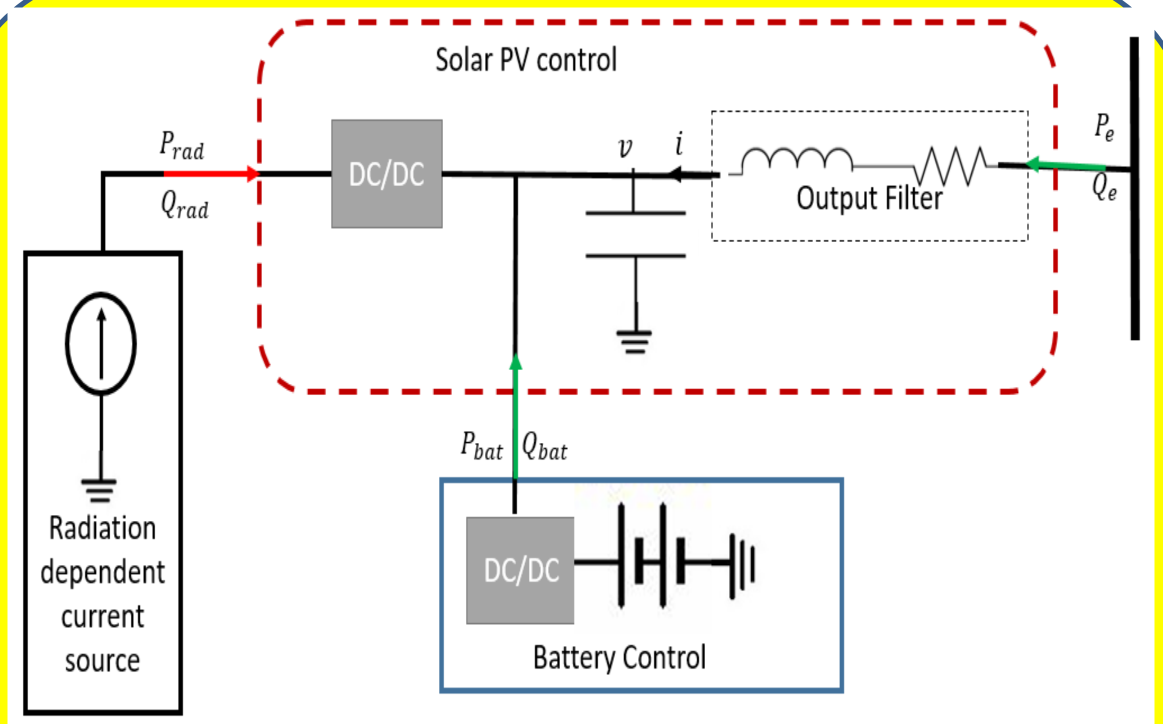
Multi-layered interactive model—ENERGY DYNAMICS



Basic R&D control challenge:

Overcoming complexity of modeling and control





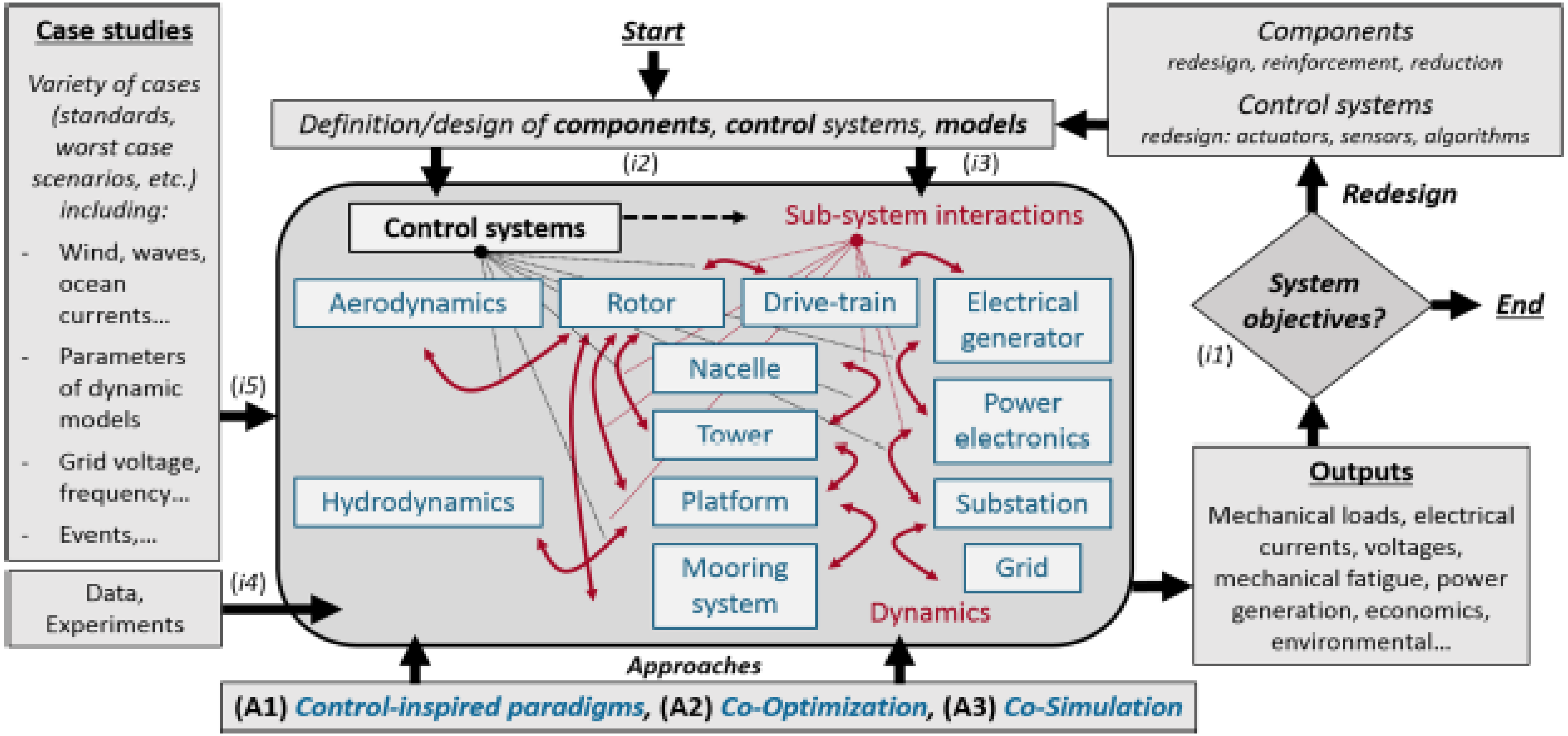
Model of solar PV droop? Starting from physics!!!

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

Control co-design in energy space

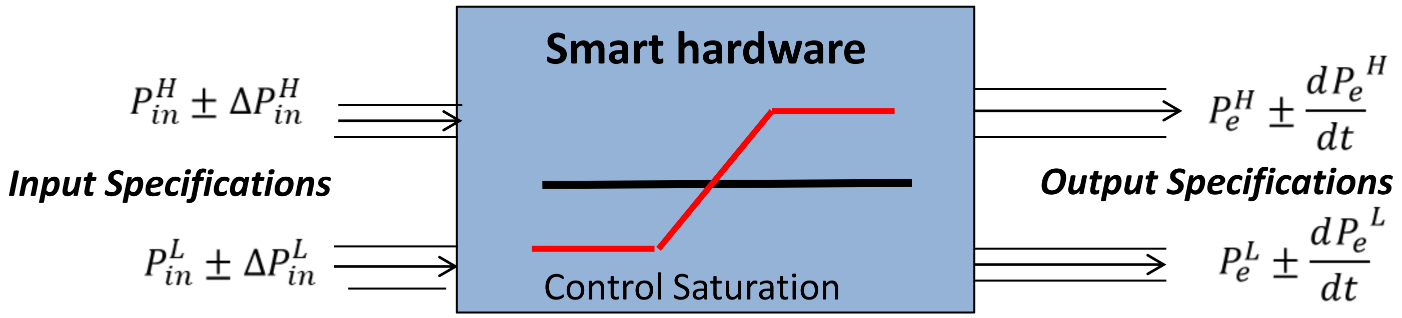
- Control co-design, and rationale for using it for microgrids
- Problem posing for co-design of Sheriff microgrid
- System design enhancements needed—hidden traps
- The co-design problem formulation in energy power space
- Unified component specifications and interaction conditions for feasible and stable service in energy space
- Case studies —1) comparison of dynamical performance with today's primary control; 2 the key role of optimal voltage dispatch

Unified control co-design concept



Garcia-Sanz, Mario. "Control Co-Design: an engineering game changer." Advanced Control for Applications: Engineering and Industrial Systems 1, no. 1 (2019): e18.

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)

Potential of plug-and-play primary/secondary controllers*

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

Marija Ilic, Xia Miao, Rupamathi Jaddivada, Aidan Dowdle, " Distributed Multi-Layer Energy-based Control for Stabilizing Microgrids", MIT-EESG Working Paper, February 5, 2017, 2017-2

*Marija Ilic, Xia Miao, Rupamathi Jaddivada, Aidan Dowdle, "*Nonlinear Control Design for Plug-and-Play Integration and Operation in Electric Energy Systems*", MIT-EESG Working Paper, February 5, 2017, 2017-3*

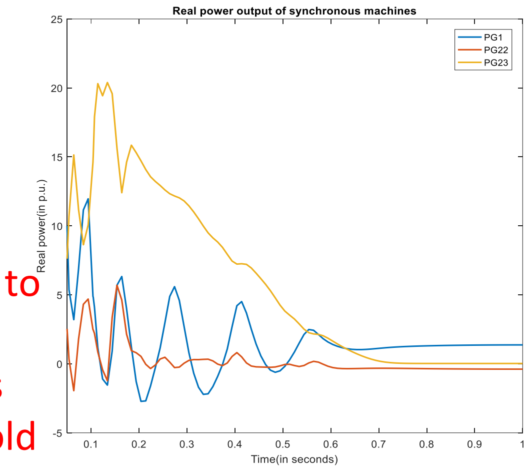
Application on Test System 1: Sheriff grid to evaluate primary control performance in systems with induction motors

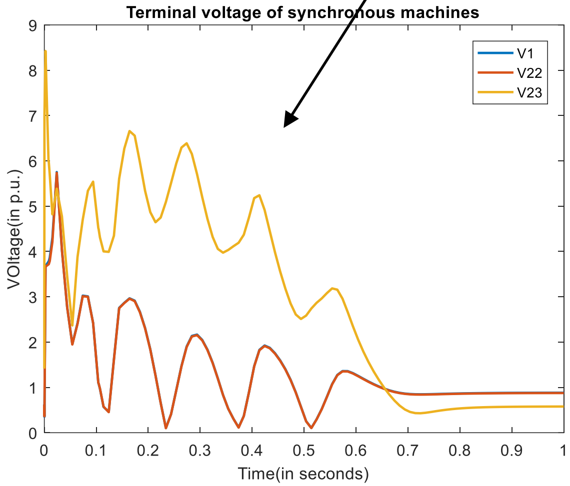
System simulated: Utility connected Sheriff with two large industry scale induction motors

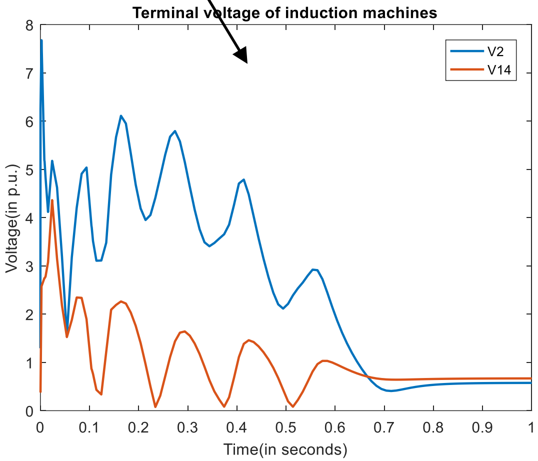
Would have damaged the machines if protection does not exist

Constant gain control

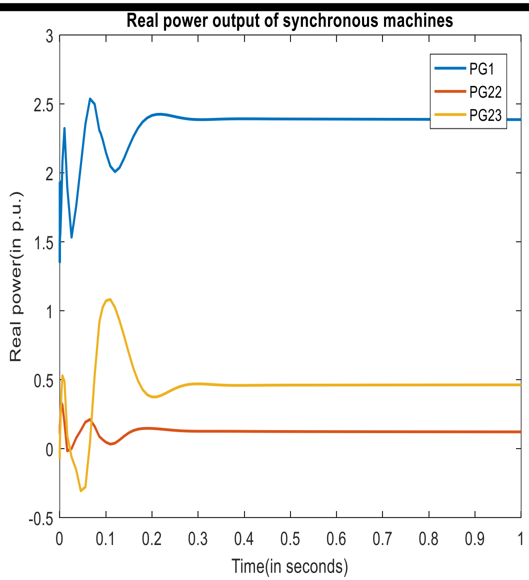
Concept of quasi-static droops used to calculate control gains might not hold here

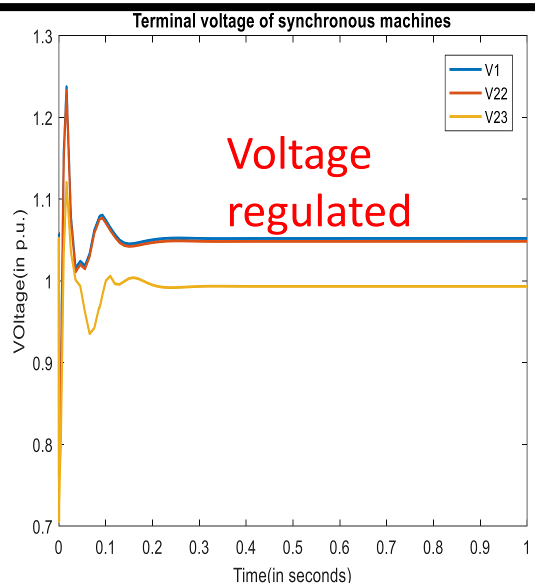




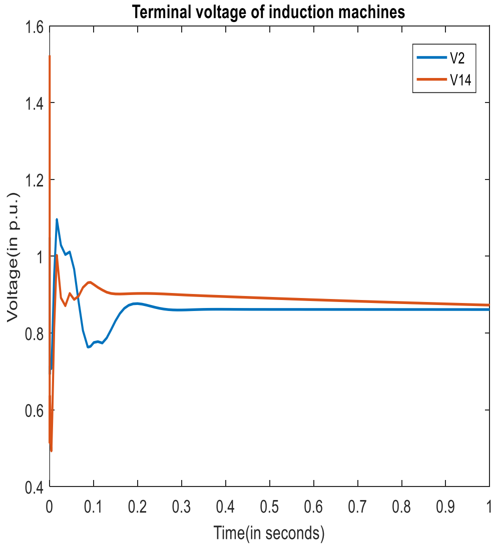


Energy based Control





Voltage regulated

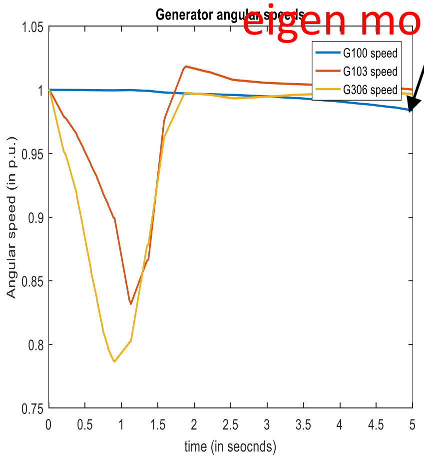


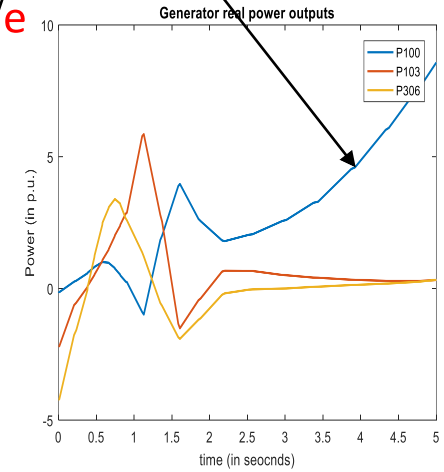
Application on Test System 2: Banshee grid-utility connected

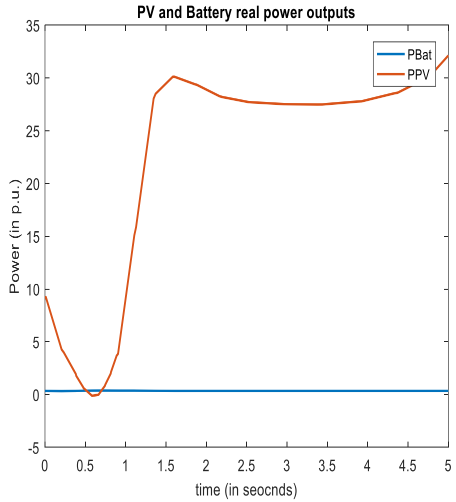
Controller implemented: 1. PV in grid following mode 2. Battery in grid forming mode

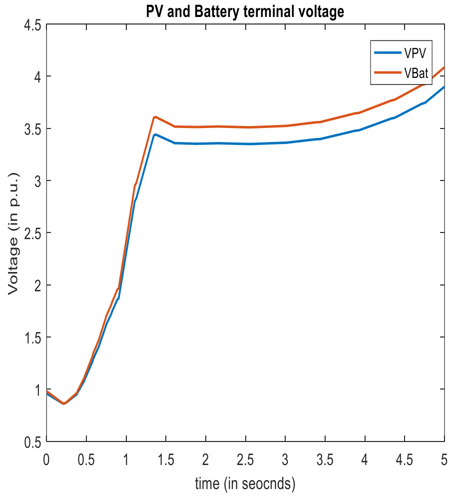
Constant gain control

One positive unstable eigen mode

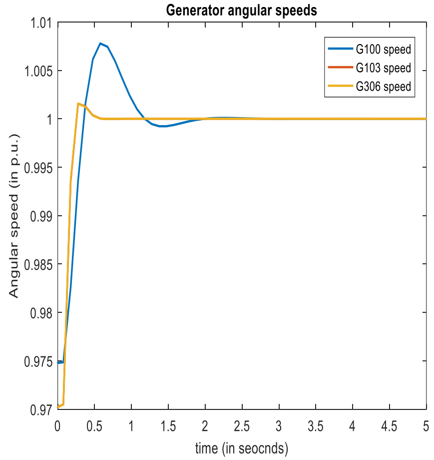


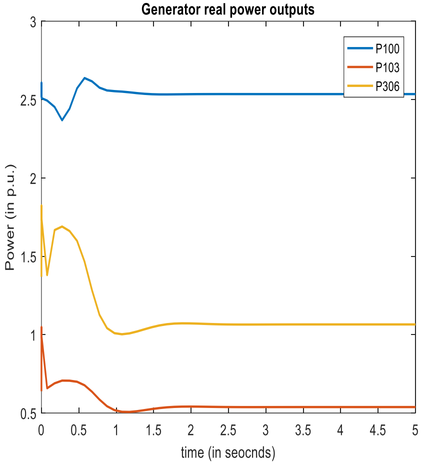


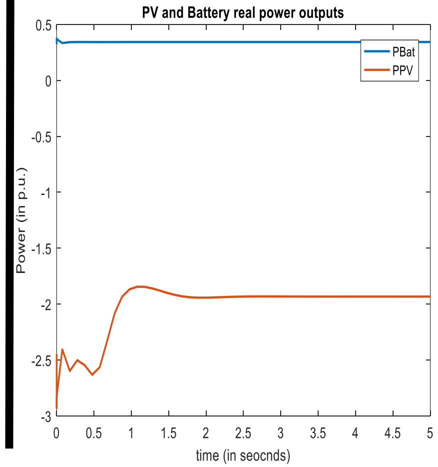


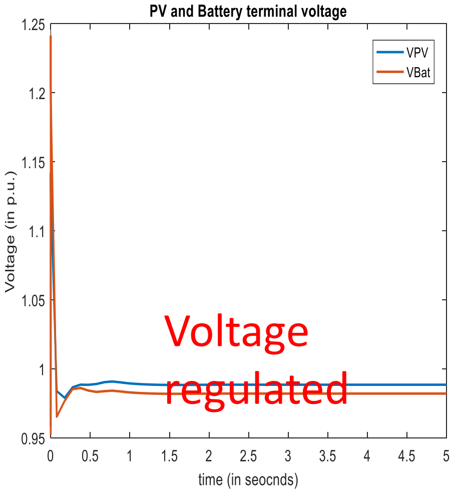


Energy based control







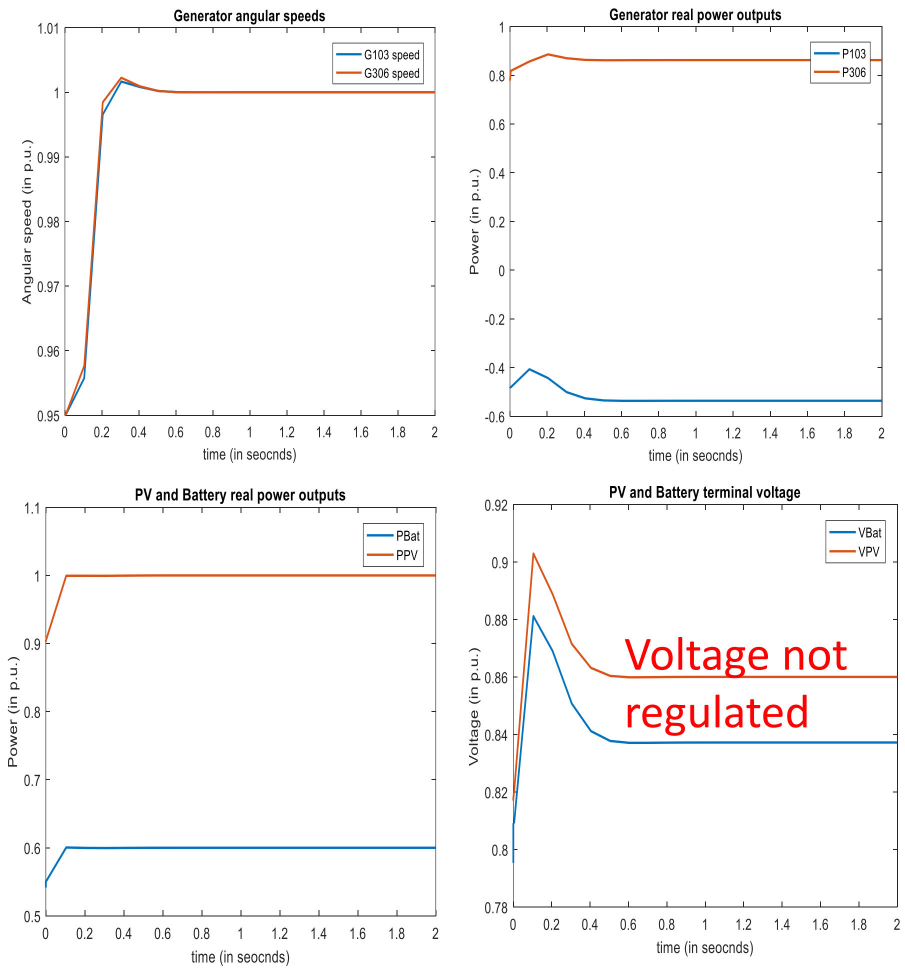


Voltage regulated

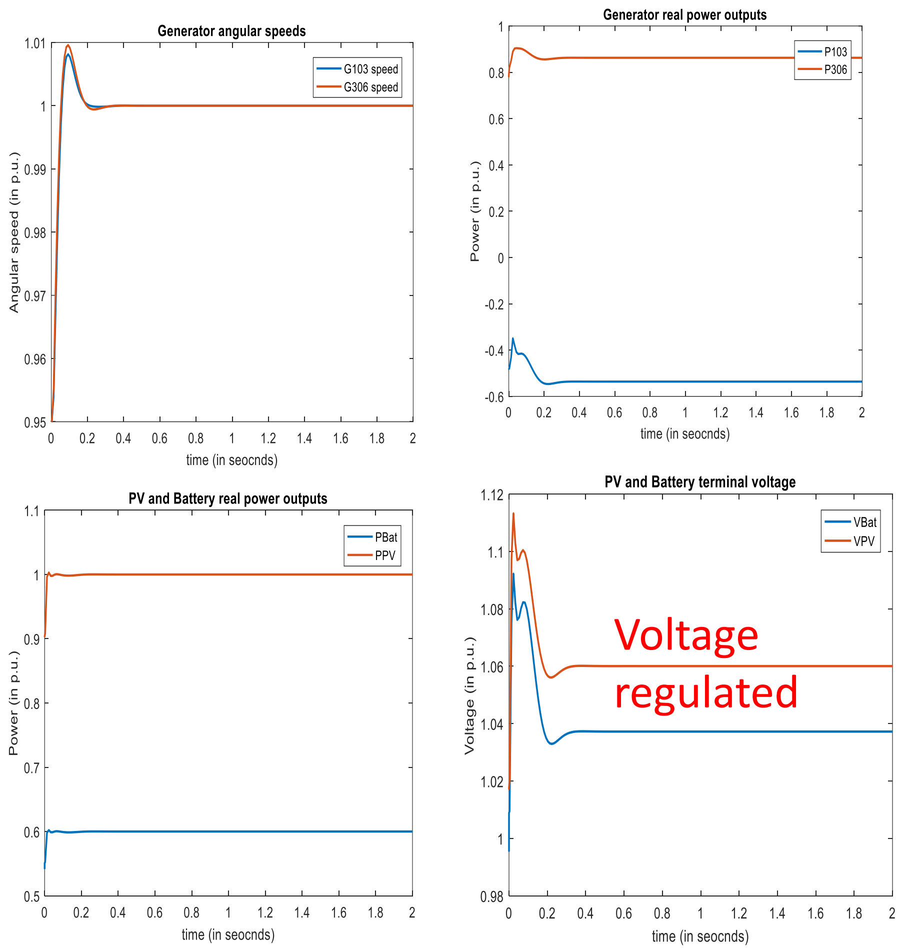
Application on Test System 2: Isolated Banshee grid

Controller implemented: 1. PV in grid following mode 2. Battery in grid following mode

Constant gain control

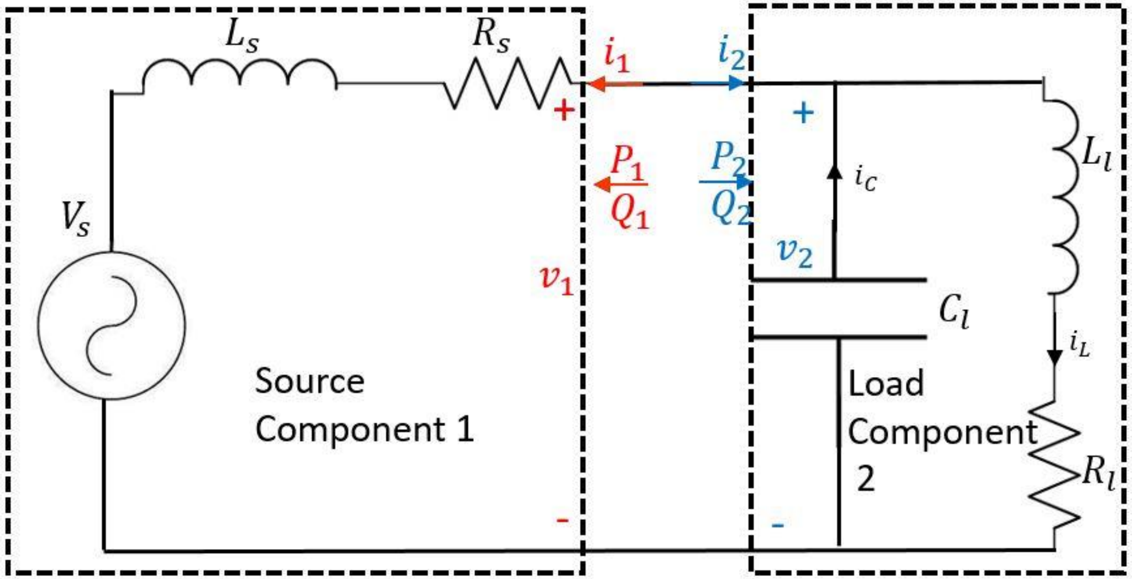


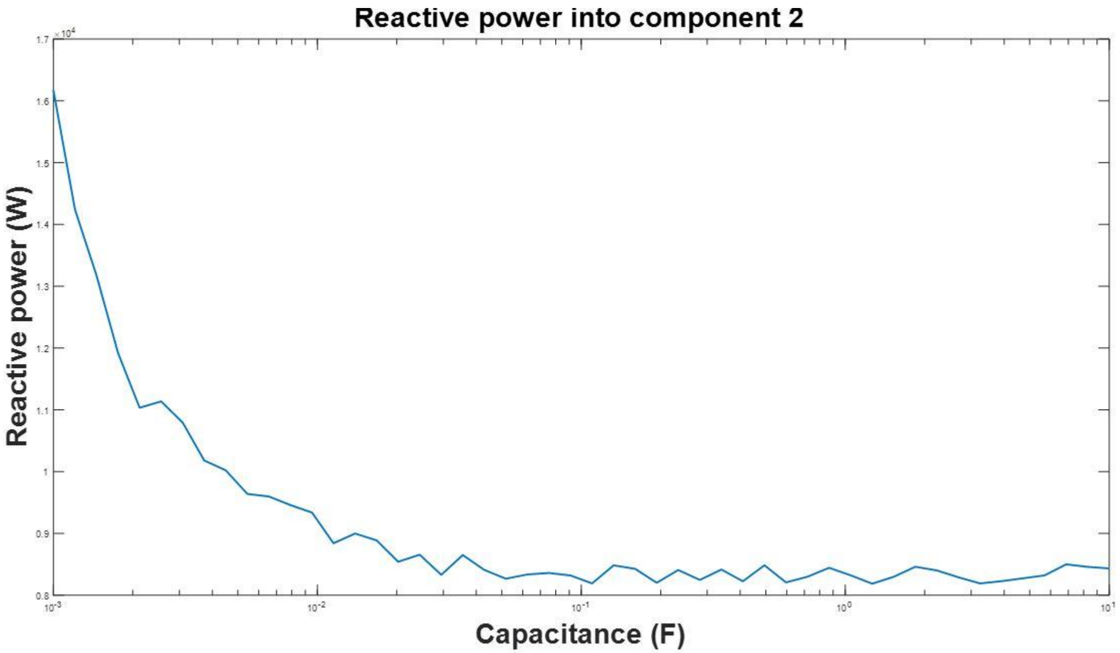
Energy based control

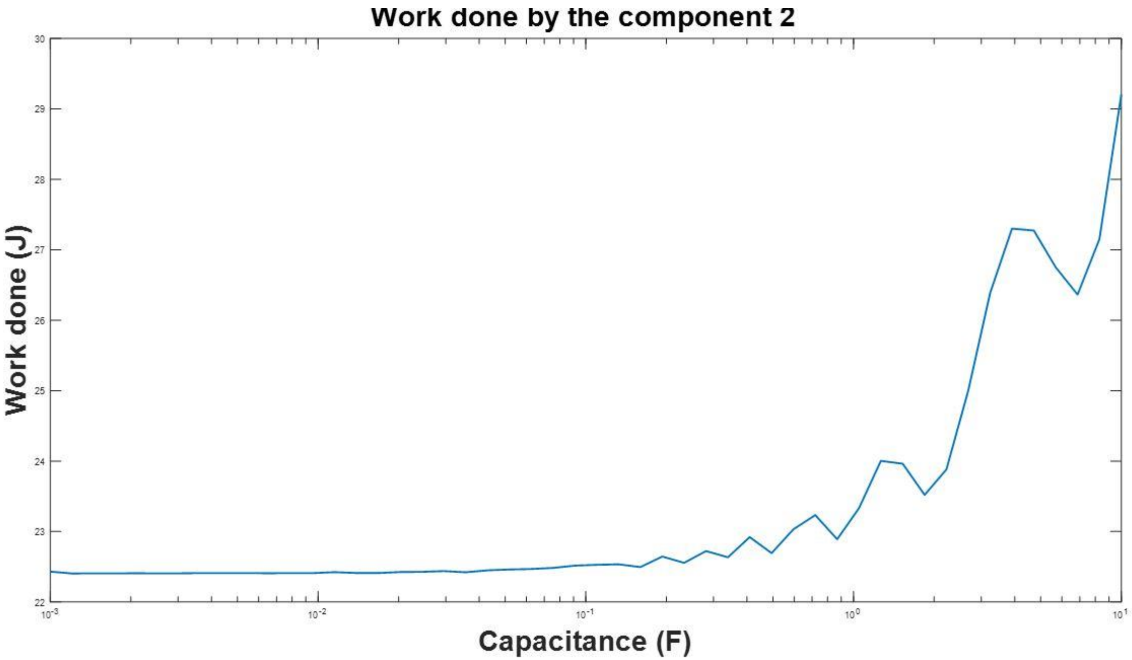


OPTIMIZATION IN ENERGY SPACE--Importance of reactive power Q for efficiency

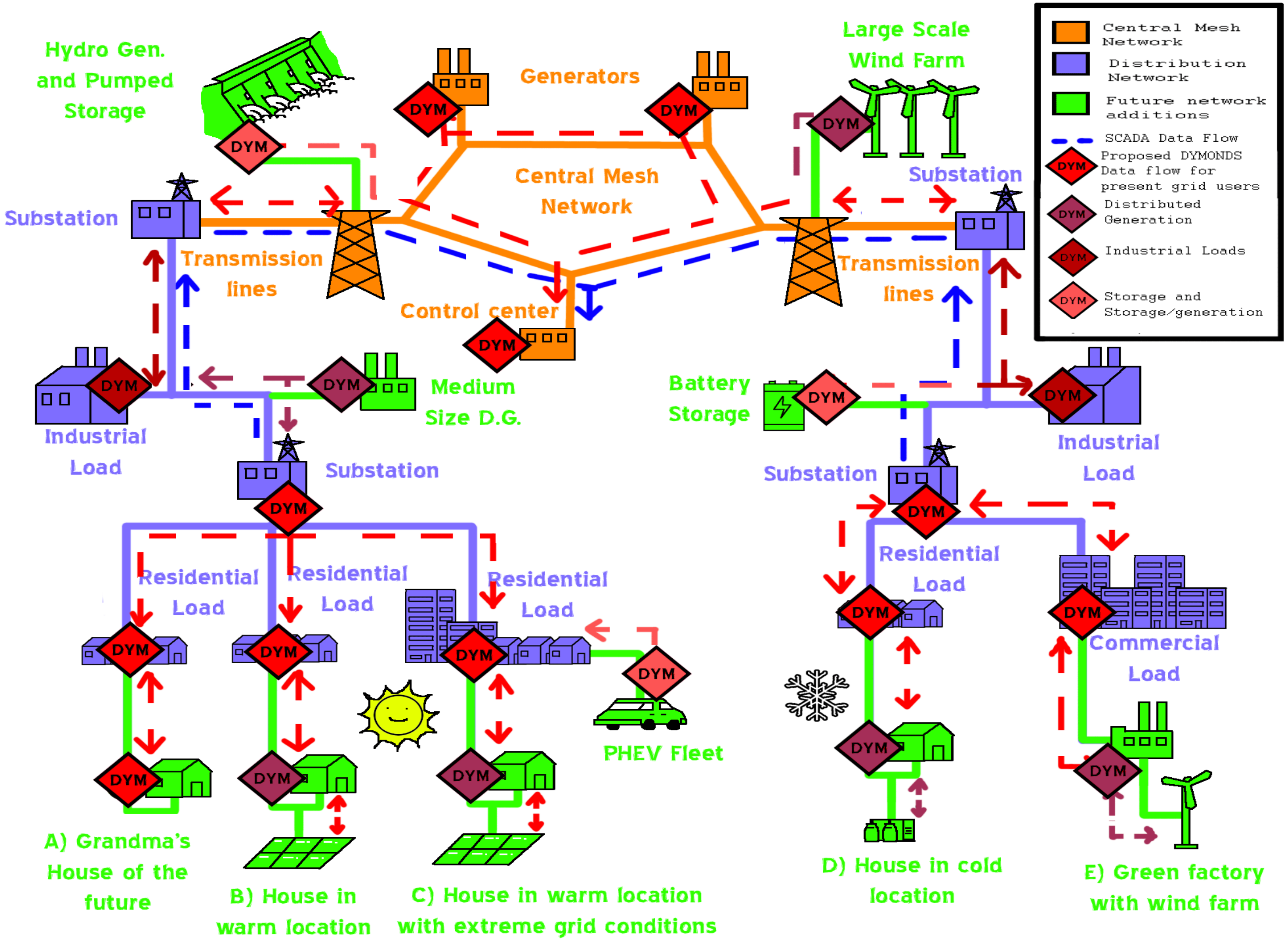
- Capturing rate at which energy can be injected into neighbors
- Candidate supply function to establish dissipativity at component level or sub-system level w.r.t stored energy in tangent space as a storage function
- Characterize inefficiency







DyMonDS: Basis for simple protocols that work*



*Ilić, M. D. (2010). Dynamic monitoring and decision systems for enabling sustainable energy services. Proceedings of the IEEE, 99(1), 58-79.
Ilic, Marija D. "Toward a unified modeling and control for sustainable and resilient electric energy systems." Foundations and Trends in Electric Energy Systems 1.1-2 (2016): 1-141.

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

Concluding thoughts

- Iterative control co-design has a great potential for enabling microgrids to meet both technical and economic performance. It should be considered.
- 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.

Concluding thoughts

- Microgrids have great potential to serve localized needs of remote end users
- They can also participate in end-to-end grid services as the availability of resources and equipment status change
- No longer possible to have pre-programmed grid protection and controllers
- DERs have generally both fast automation and model predictive decisions
- Recent R&D results indicate that much can be done in an entirely distributed interactive way through minimal information exchange; autonomous grids?
- Unified protocols for characterizing DERs in energy space and testing conditions using coarser models to ensure interactions conditions (for details, see

Paper Title: Architectures to support deployment of microgrids at multiple values, Paper Number: 20PESGM3515 ;

Paper Title: Microgrid control co-design for feasible and stable operations during large variations in system conditions

Paper Number: 20PESGM2297

Conclusions

- Novelty of MIT's TE approach
  - Quasi-static physics-based coupled droop relations derived and integrated in the TE agents
  - Framework for bidding designed for achieving implementable real and reactive power bids, in response to real power prices and voltage violation penalties.
  - Advanced optimal power flow solver optimizes voltage deviations used
  - Multi-rate simulations supporting the composite control design with the bidding layer at the slowest timescale and control adjustments mapped to real and reactive power adjustments at multiple time scales through the closed-loop generalized droop relations.

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