Three different ways of integrating IBRs: What do we know and what is tradeoff”

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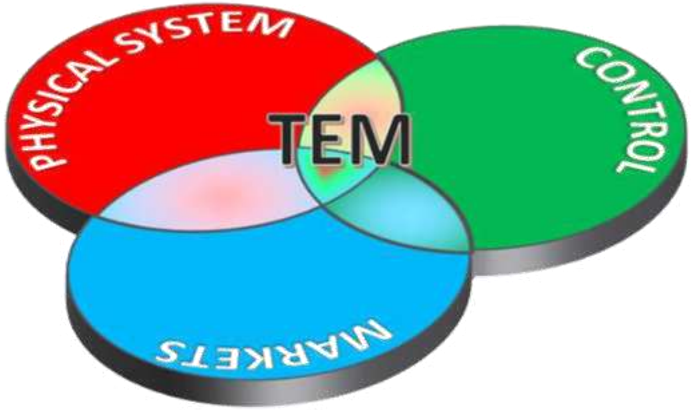
Workshop on Enabling Cyber-Secure Distribution Systems with Edge IBRs

MIT, October 19,2024

Outline

- A long-standing R&D problem: On-line data-enabled computing for supporting operations during normal and abnormal system conditions
- Emerging challenge: Computing for flexible data -enabled clean and resilient energy utilization
- As basic as it gets: How to operate power grids with new supply-demand mix reliably and efficiently? Which software? Which computer platforms? Key role of embedded automation.
- Multi-layered modeling: From data to minimal information exchange for interactive operations (DyMonDS)
- Need for distributed coordinated data-enabled architectures (taking the effects of grid-edge DERs/IBRs)
- Lessons learned using MIT SEPSS (now evolving into DDT)

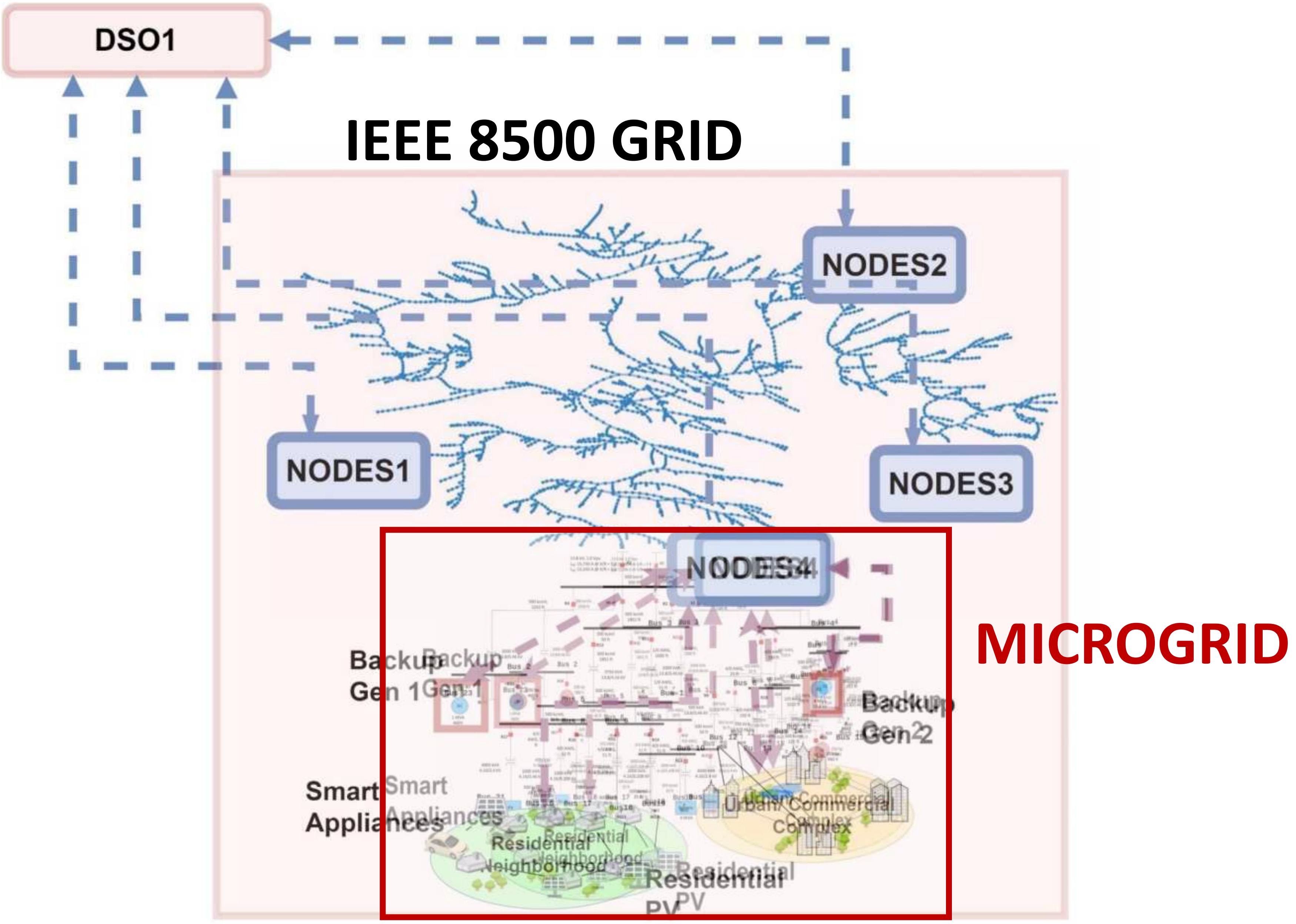
PECAN STREET, INC DEVELOPING SOLAR CONGESTION SOLUTIONS IN RESIDENTIAL AREAS



Ilic MD, Joo JY, Andrews BW, Raghunathan B, Benitez D, Maus F, inventors; Robert Bosch GmbH, assignee. Adaptive load management: a system for incorporating customer electrical demand information for demand and supply side energy management. United States patent US 10,755,295. 2020 Aug 25.

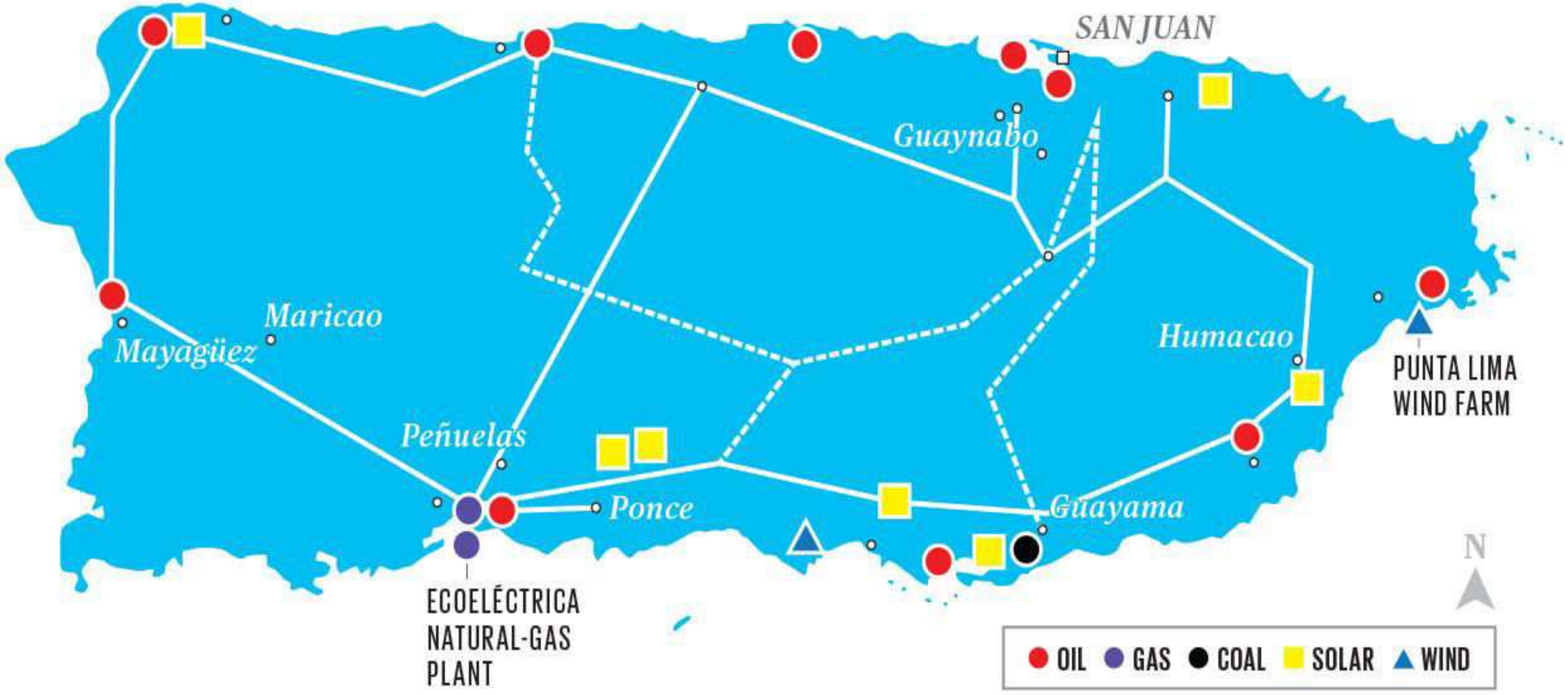
M.D. Ilic and Jaddivada, R., “Methods and Systems for Secure Scheduling and Dispatching Synthetic- regulation Reserve from Distributed Energy Systems,” United States of America Patent No. 11223206, Issued January 11, 20

M.D. Ilic, Miao, X. and Jaddivada, R., “Plug-and-Play Reconfigurable Electric Power Microgrids,” U.S. Patent 10,656,609, issued May 19, 2020.



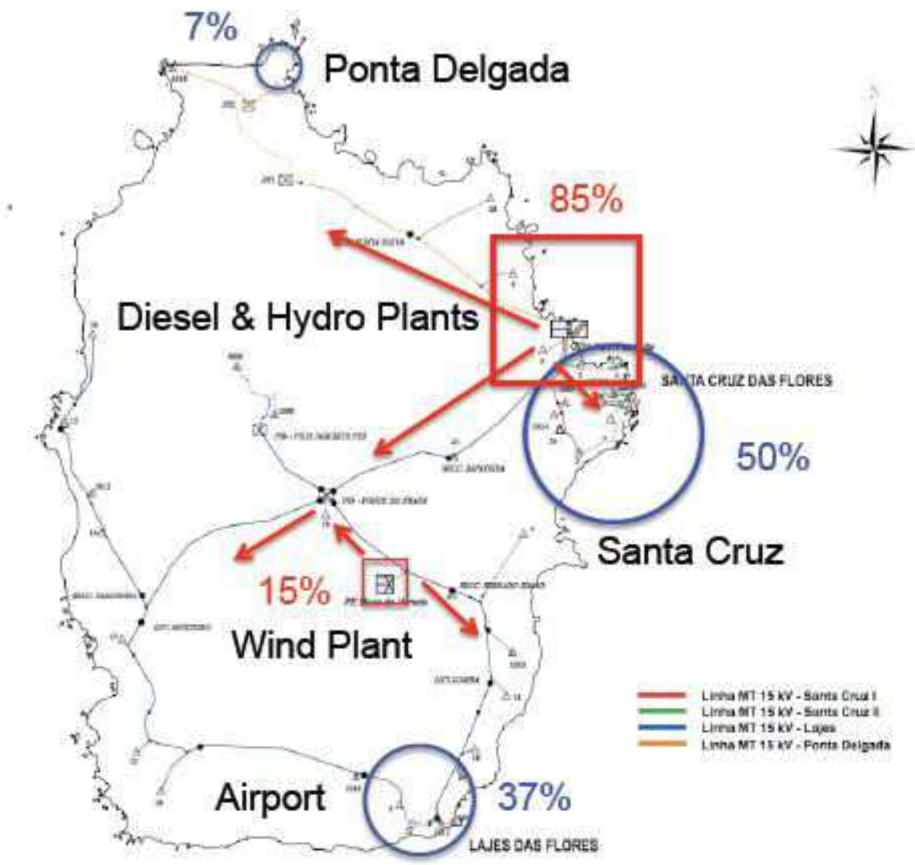
DSO1
IEEE 8500 GRID
NODES2
NODES1
NODES3
NODES4
MICROGRID
Backup Gen 1
Backup Gen 2
Smart Appliances
Residential Neighborhood
Urban Commercial Complex
Residential PV

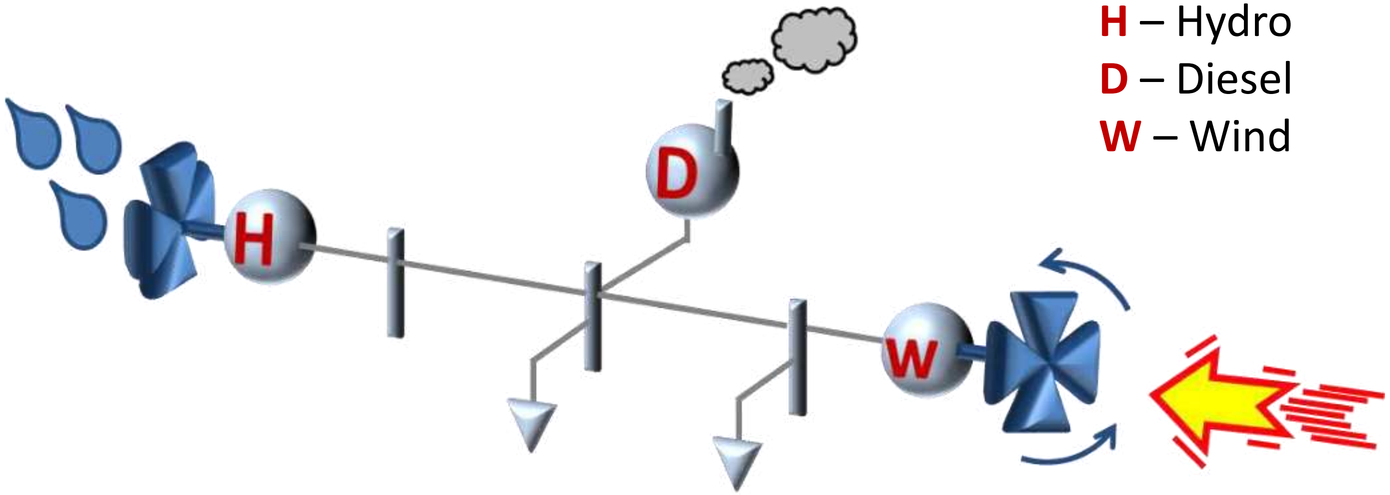
Electric power grids in islands



Puerto Rico
Efficient, clean, resilient?

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





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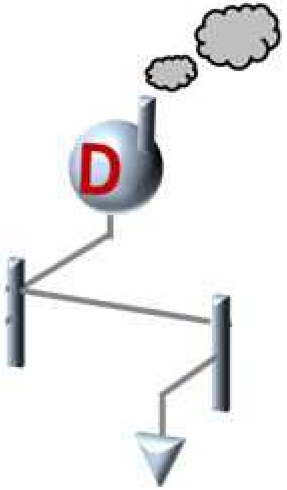
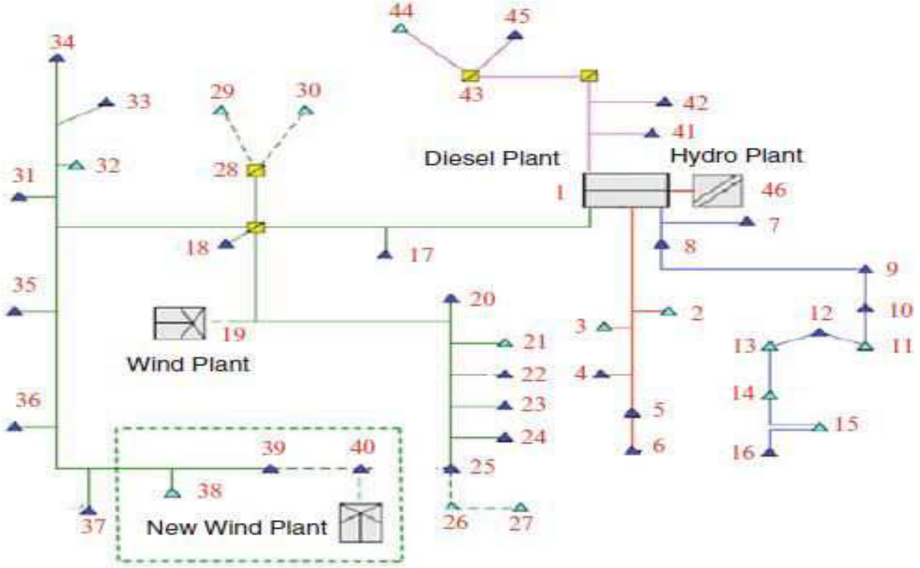


To?



*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.

Complexity of emerging microgrids

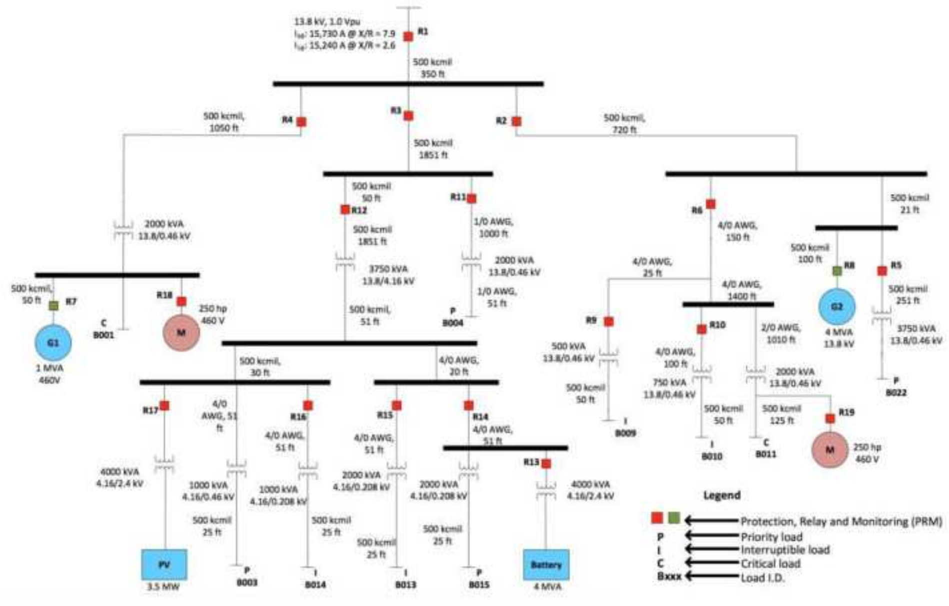


Fig 1 Diverse loads, different priorities/dynamics

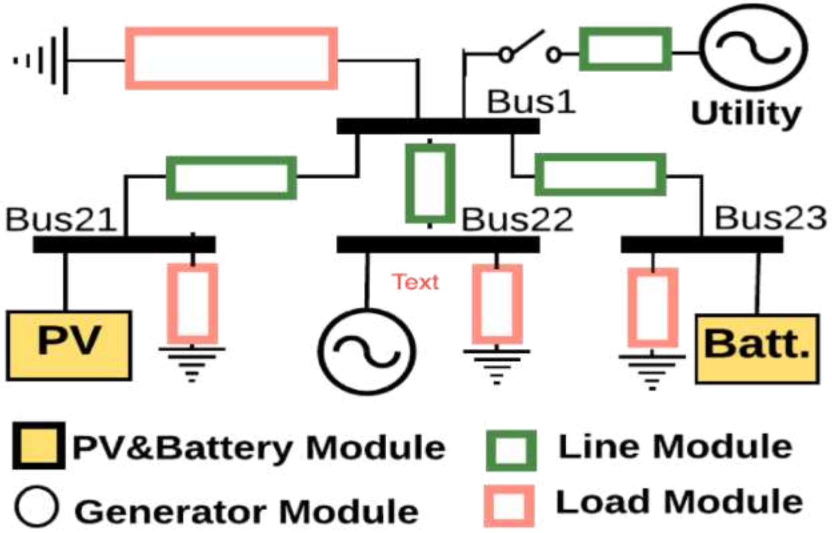


Fig 2 Heterogenous resources

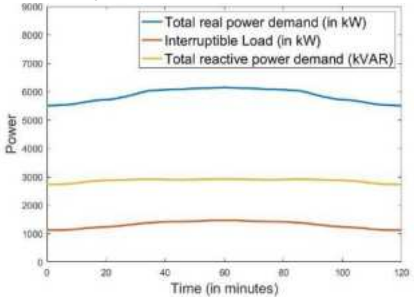
Sheriff microgrid– IEEE test system

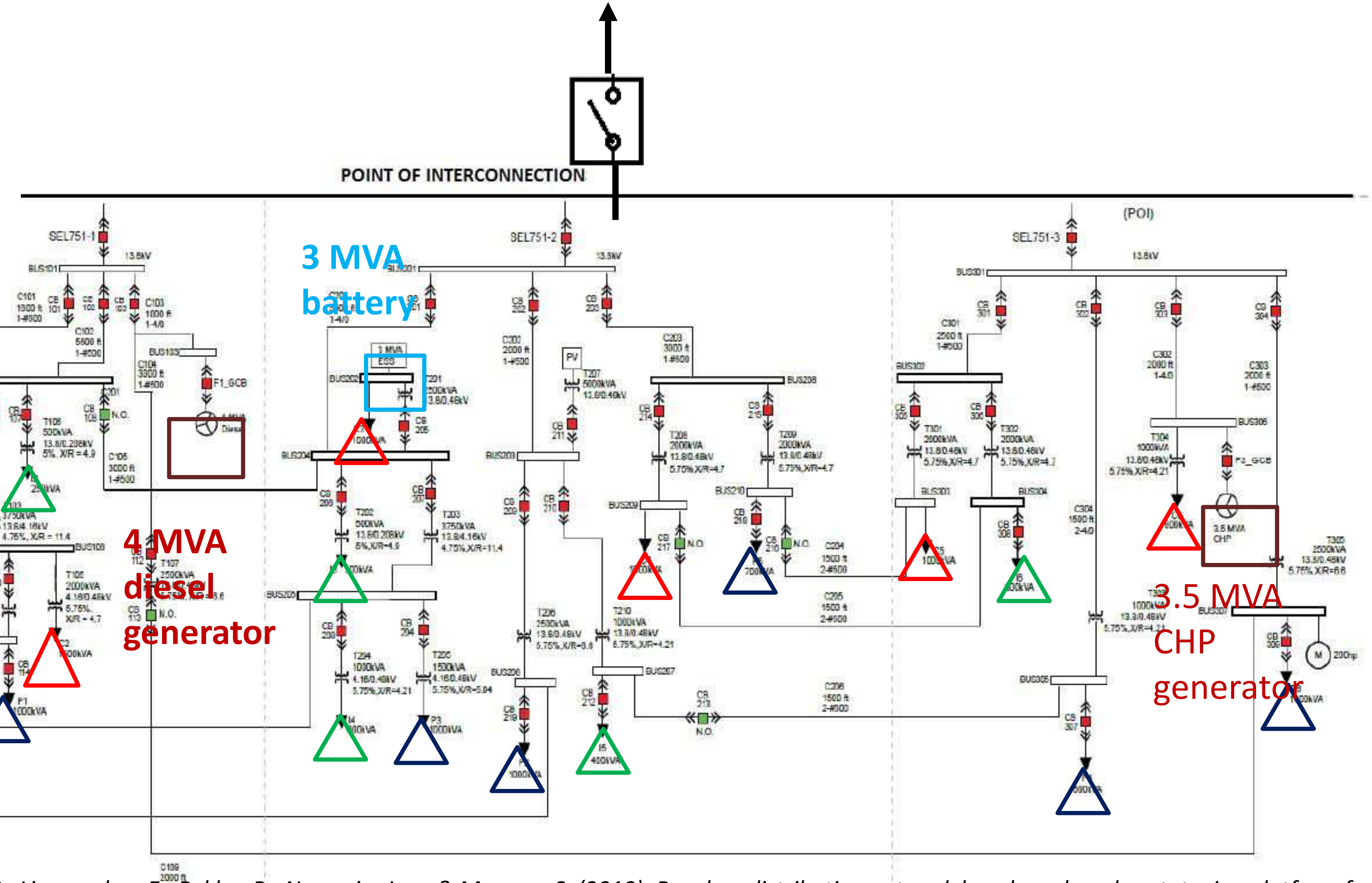
Limpaecher, E., R. Salcedo, E. Corbett, S. Manson, B. Nayak, and W. Allen. "Lessons learned from hardware-in-the-loop testing of microgrid control systems." In CIGRE US National Committee 2017 Grid of the Future Symposium, 2017.

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

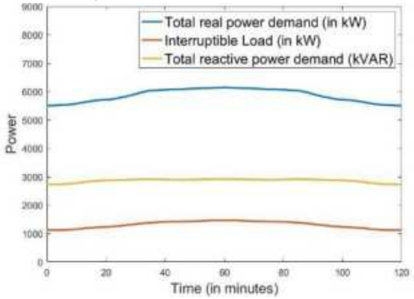


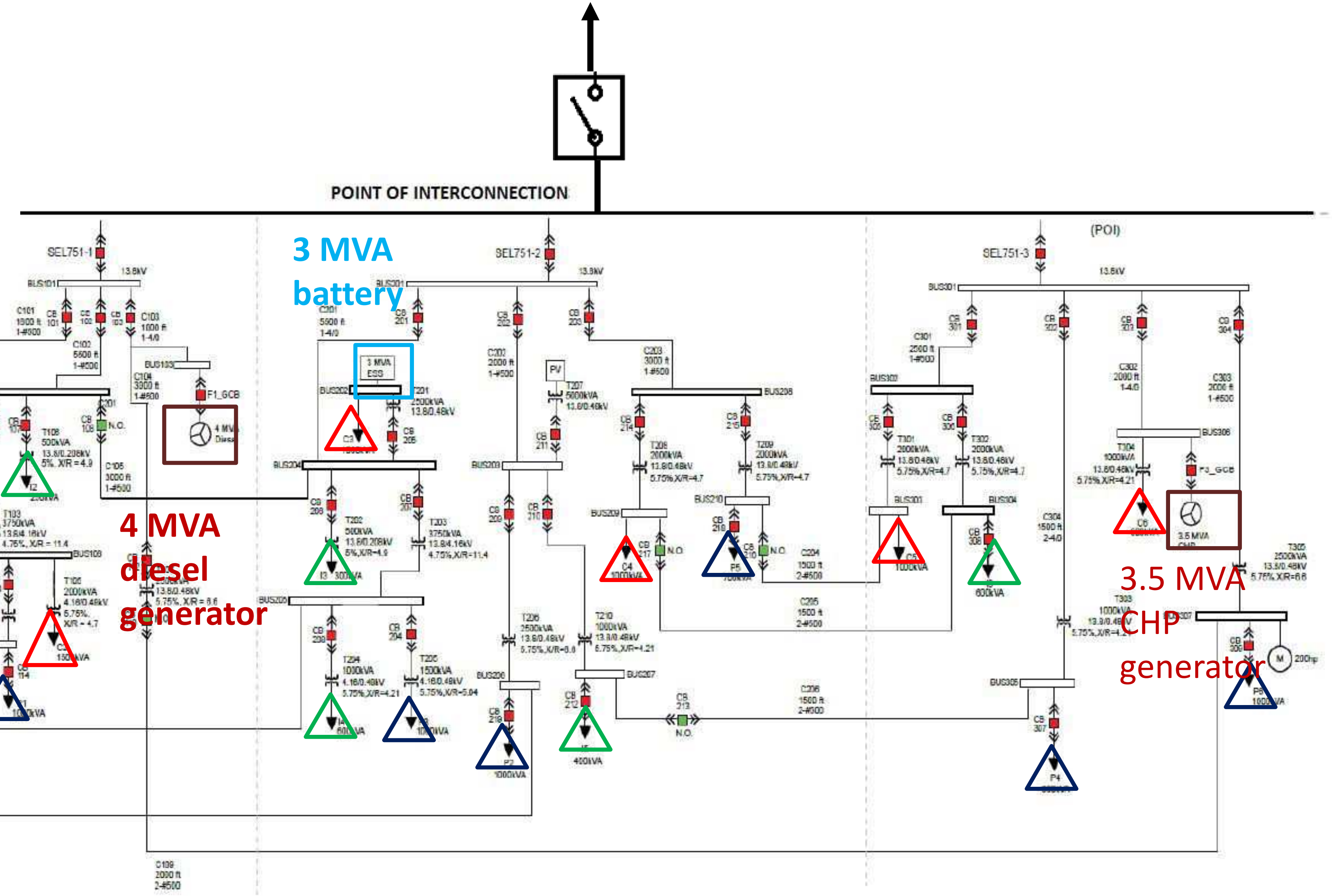


Salcedo, R., Corbett, E., Smith, C., Limpaecher, E., Rekha, R., Nowocin, J., ... & Manson, S. (2019). Banshee distribution network benchmark and prototyping platform for hardware-in-the-loop integration of microgrid and device controllers. The Journal of Engineering, 2019(8), 5365-5373.

Effect of new technologies

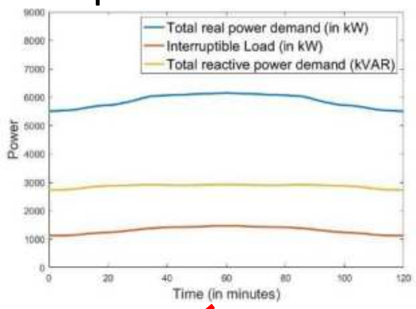
Sample Load Profile



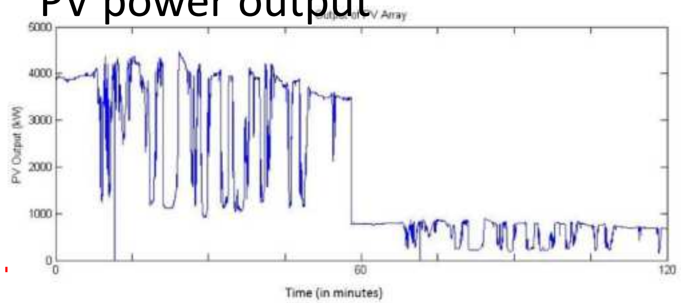


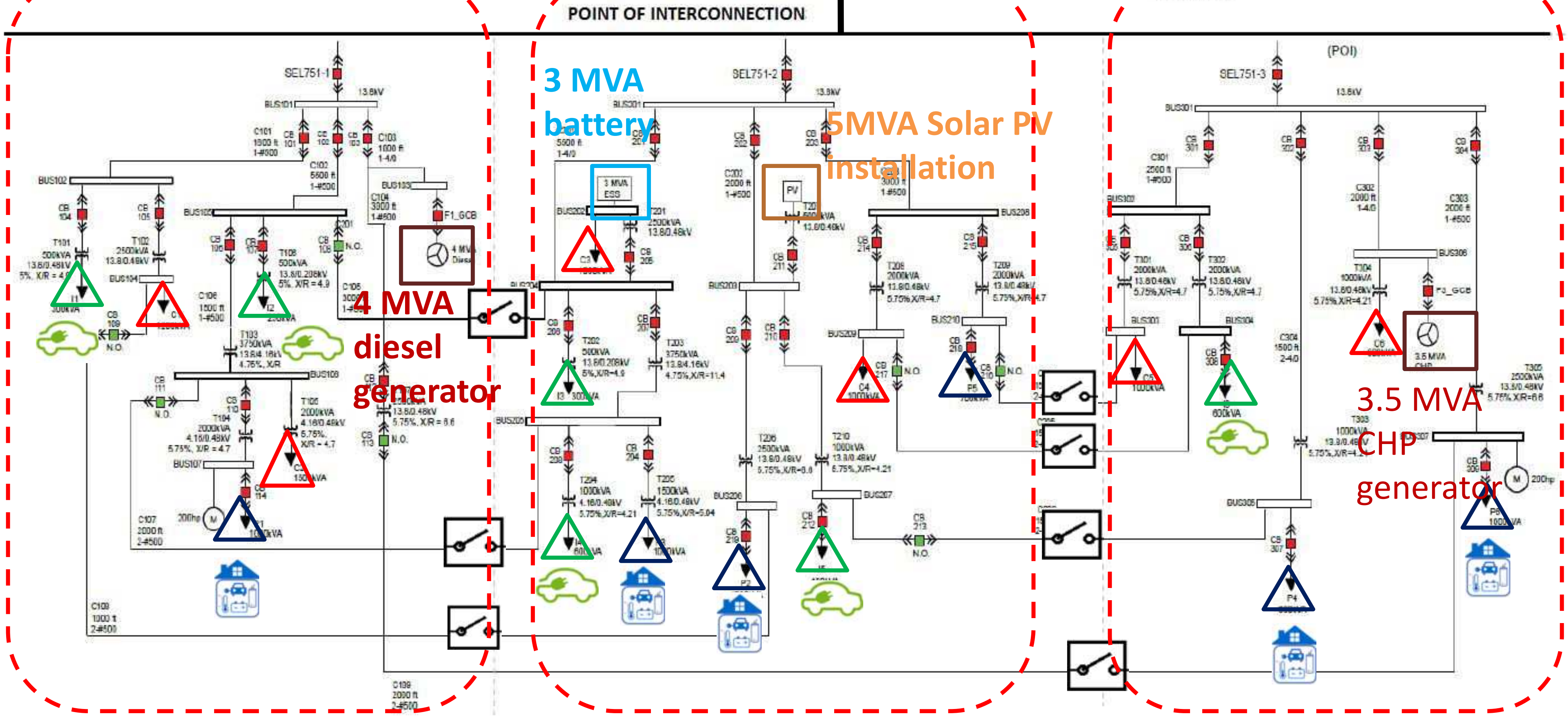
Evolution of such feeders

Sample Load Profile



PV power output





CRITICAL LOADS

PRIORITY LOADS

Interruptible LOADS

Existing and emerging challenges/needs

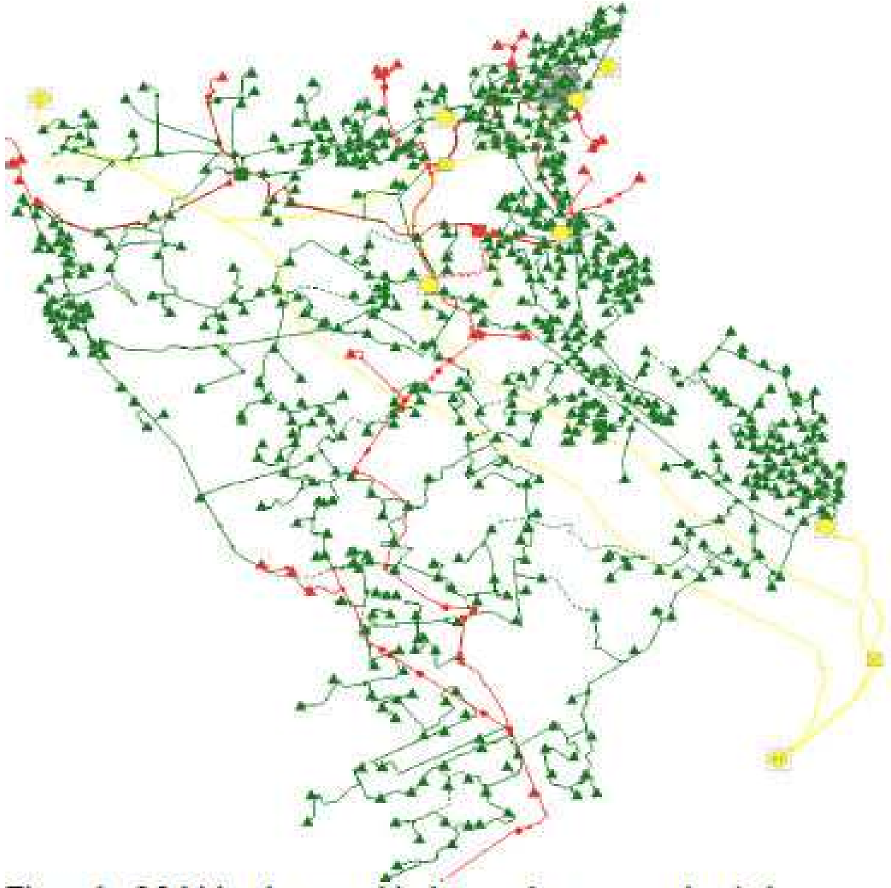


Figure 1 – Multi-level geographical network representation (sub-transmission at 60kV in yellow, and distribution at 30kV in red and 15kV in green).

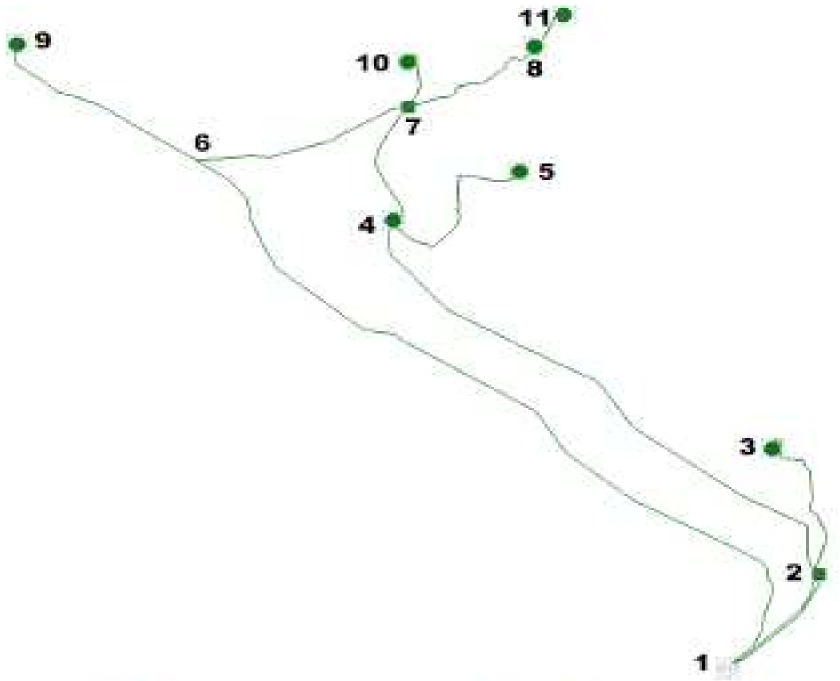


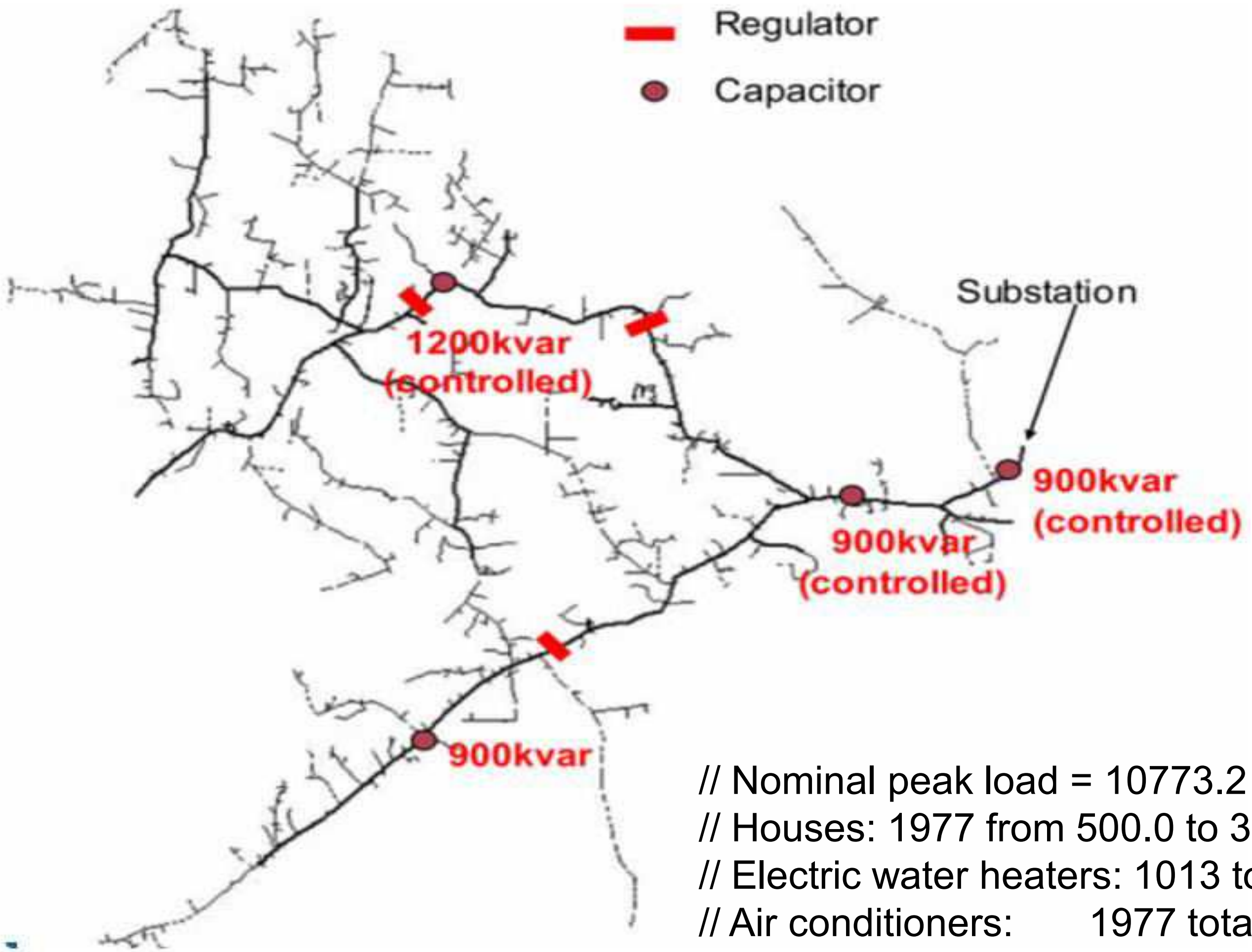
Figure 2 – Sub-transmission 60kV geographical network representation with current filter enabled (green means currents are below cable rating)

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

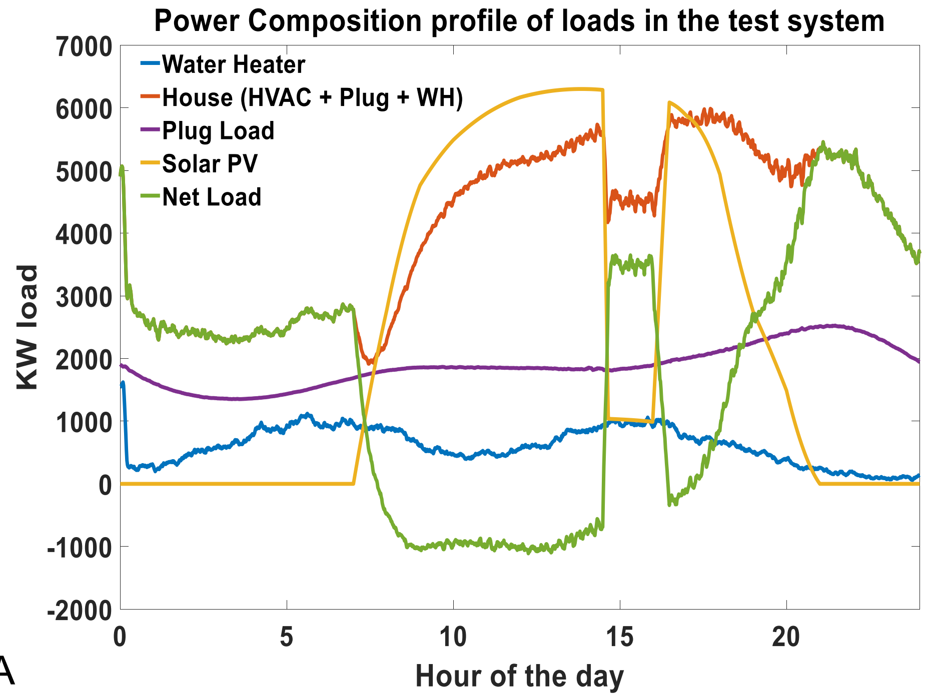
Ilic, M., Joo, J. Y., Carvalho, P. M., Ferreira, L. A., & Almeida, B. (2013, August). Dynamic monitoring and decision systems (DYMONDS) framework for reliable and efficient congestion management in smart distribution grids. In *2013 IREP Symposium Bulk Power System Dynamics and Control-IX Optimization,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

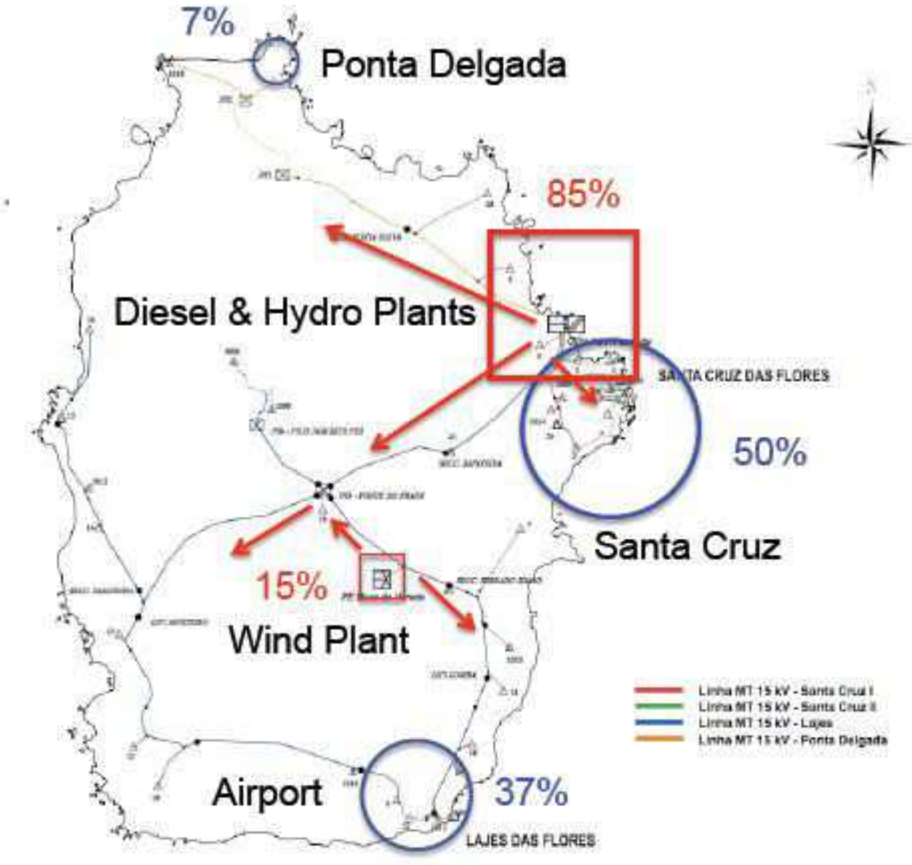
Overall technical challenge

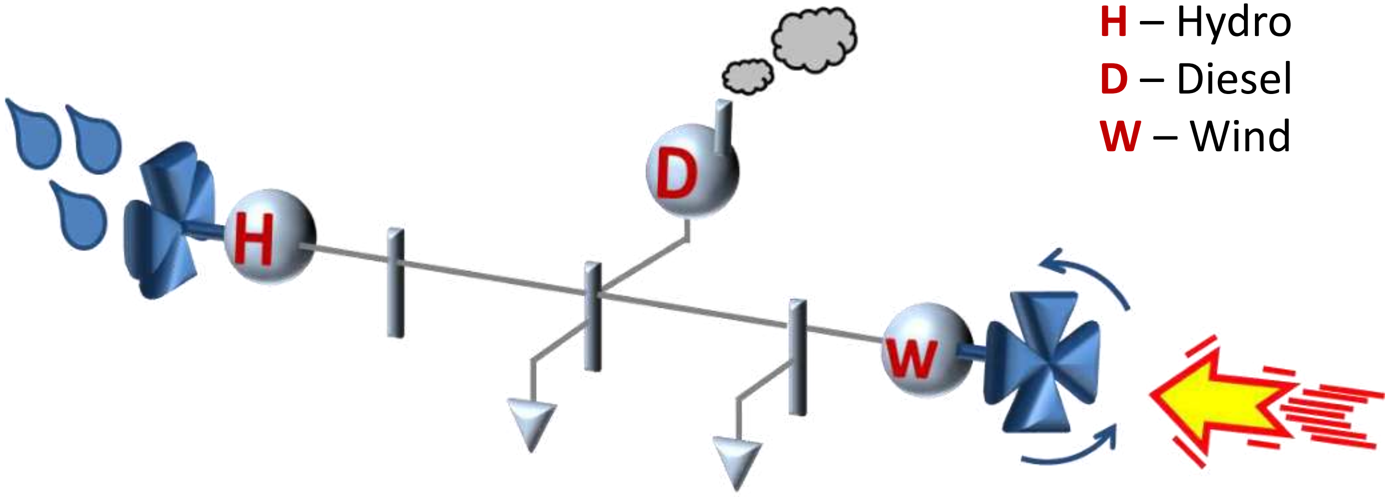
- **Need systematic tools to assess operating problems**

--***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

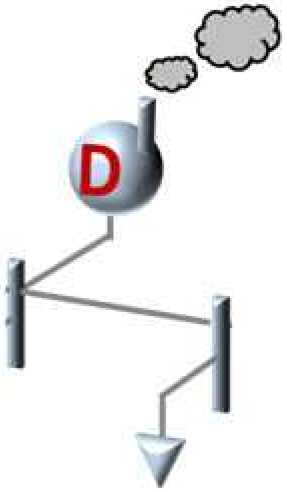
Flores Island Power System-Typical micro-grid of the future*



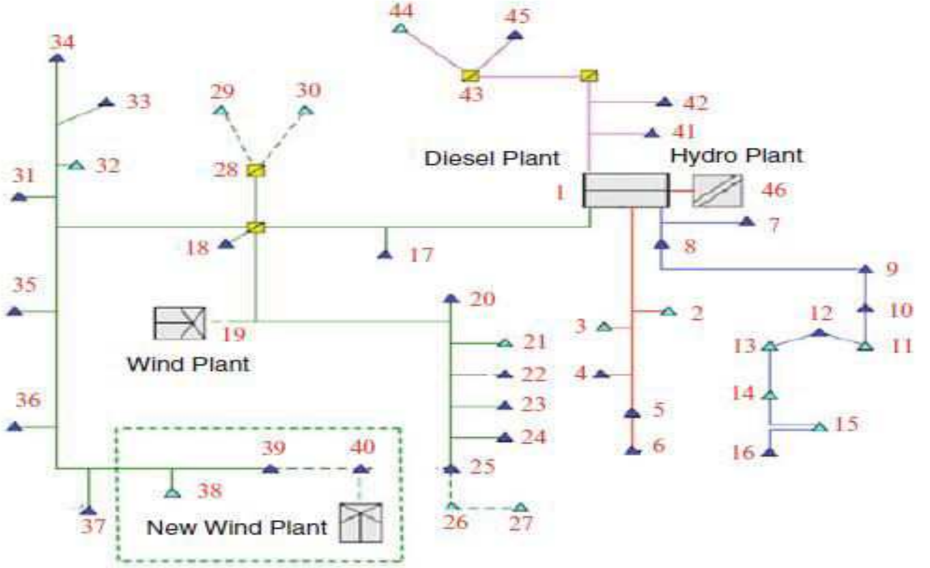


H – Hydro
D – Diesel
W – Wind

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.

Effects of microgrid controller (AC OPF-based)

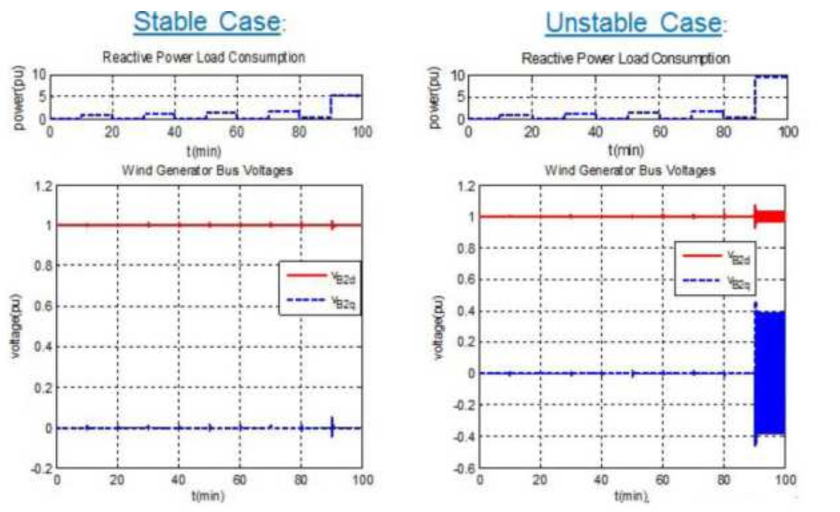
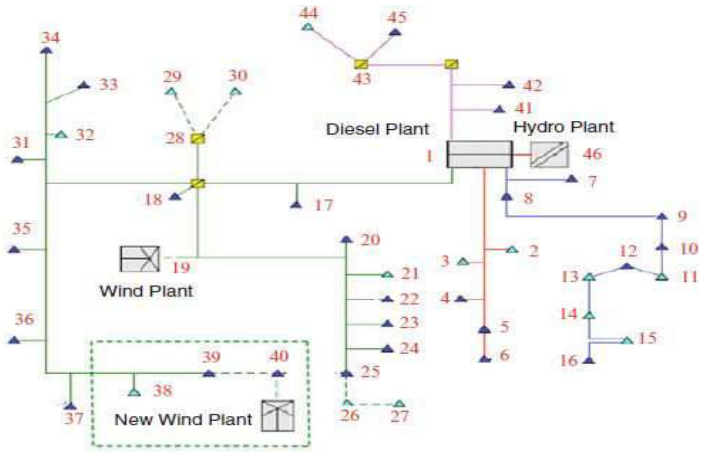


Fig. 33. Simulation results demonstrating that the reactive power set points are crucially important to the dynamic stability of the system



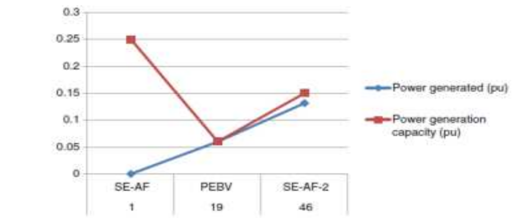


Fig. 13.3 Geographical distribution of optimal generation in Flores, wind power O&M cost 88 $/MWh

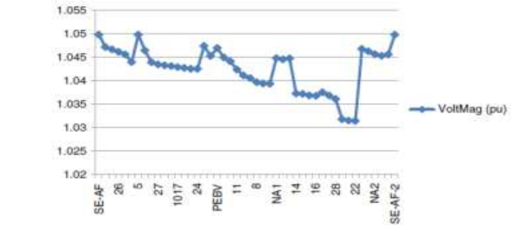


Fig. 13.4 Geographical distribution of optimized voltages in Flores, wind power O&M cost 88 $/MWh

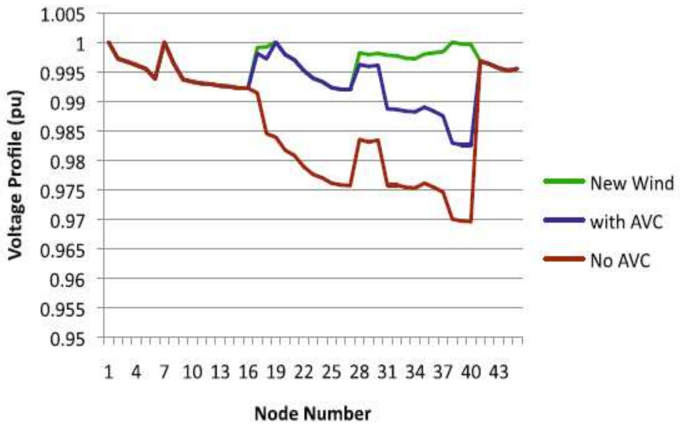


Fig. 12.6 Voltage profile of the island in three different scenarios

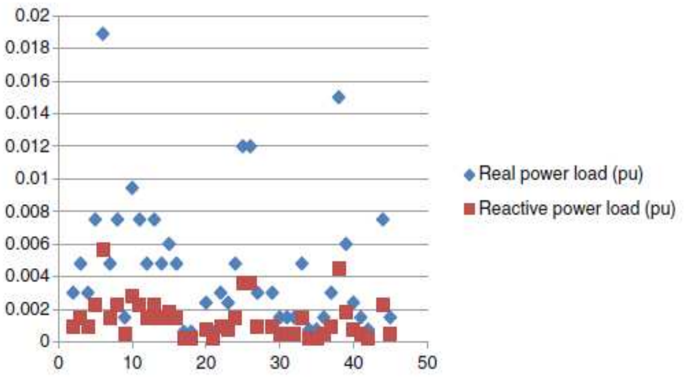


Fig. 13.2 Geographical distribution of load in Flores; the *x*-axis is the bus number 1–46; the *y*-axis is load in per unit (pu)

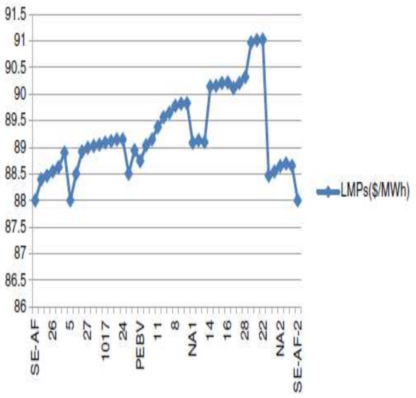


Fig. 13.5 Geographical distribution of LMPs in Flores; wind power O&M cost 88 $/MWh

Potential to add PVs and support them with EVs

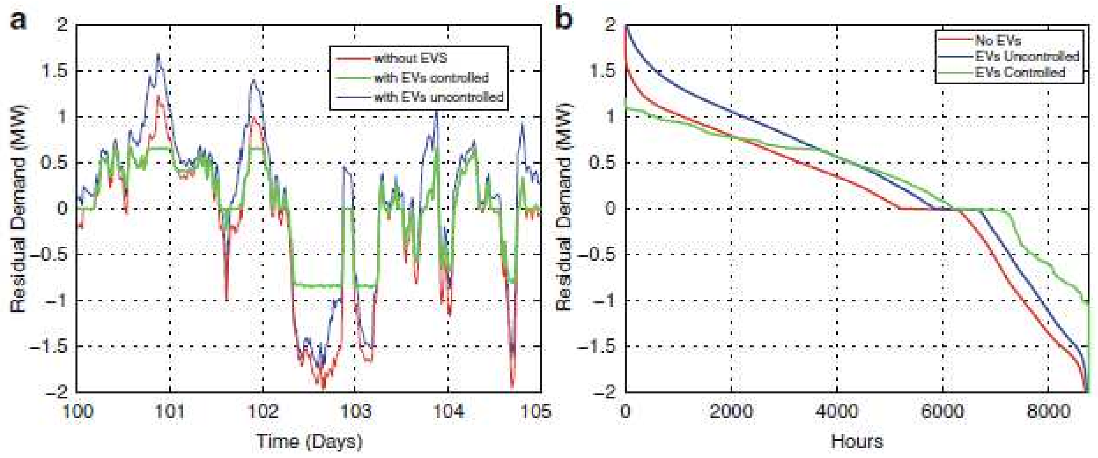


Fig. 11.9 Residual demand in three scenarios for the moderate wind and solar scenario and 1,000 EVs in a 5-day spring period (a) and the load duration curves (b)

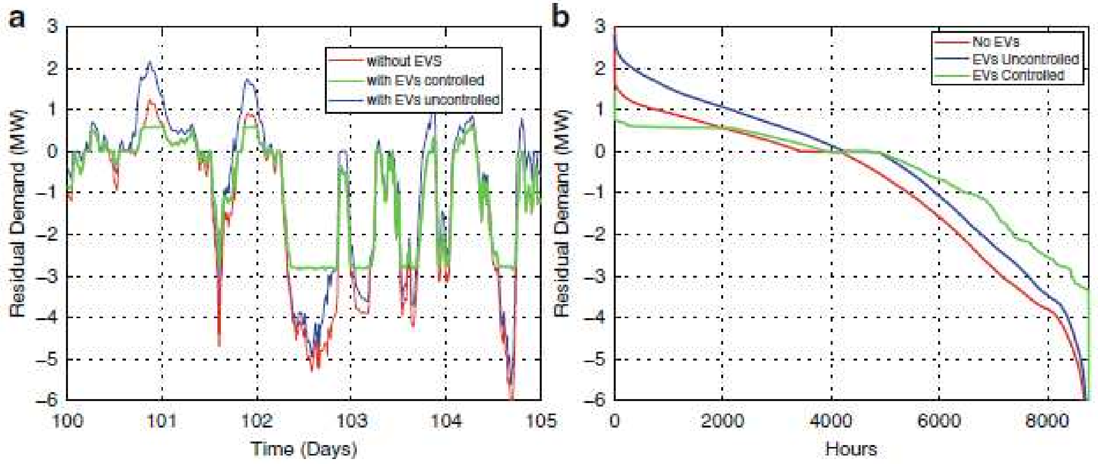


Fig. 11.11 Residual demand for the maximum wind and solar scenario and 2,000 EVs in a 5-day spring period (a) and the load duration curves (b)

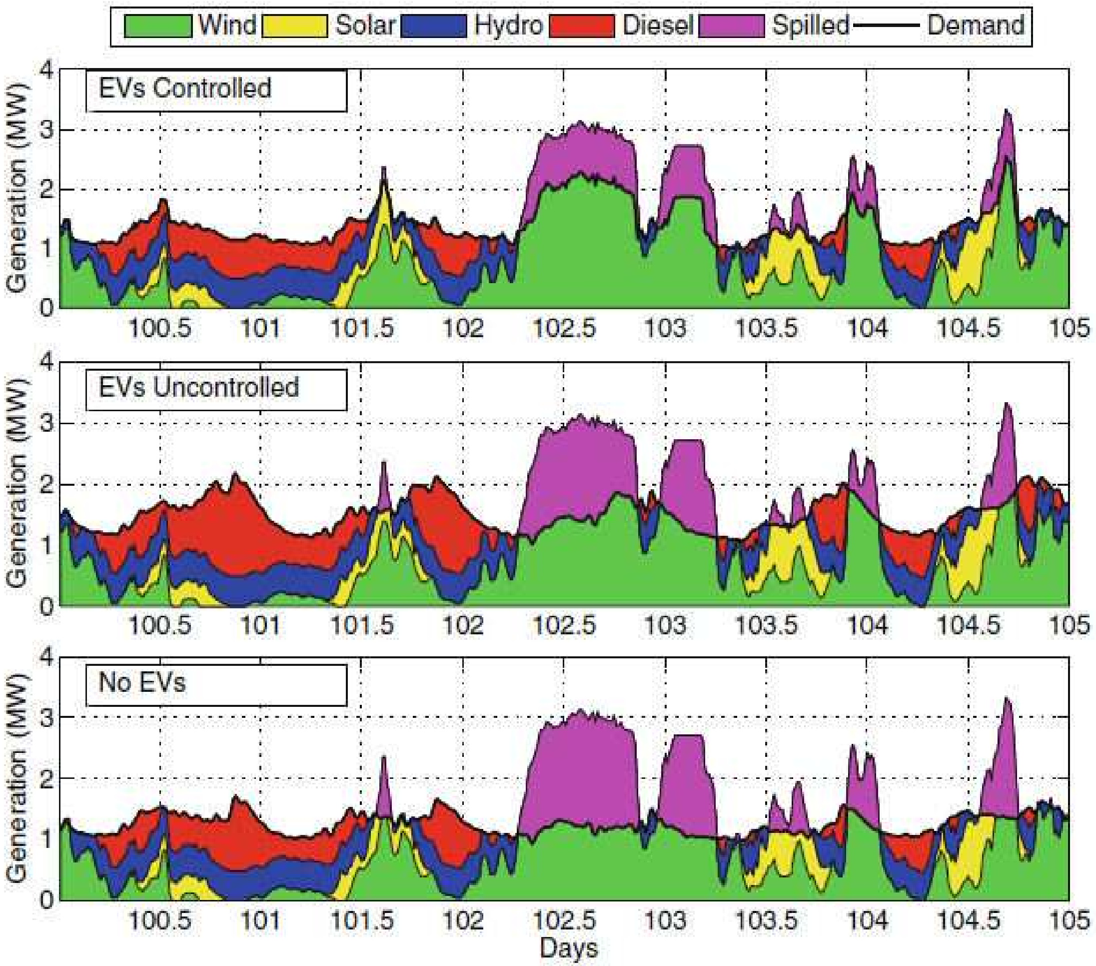


Fig. 11.10 Use of different generation types for a period in spring with 1,000 EVs in different scenarios for the case with moderate wind and solar

Major concern: Frequency regulation?

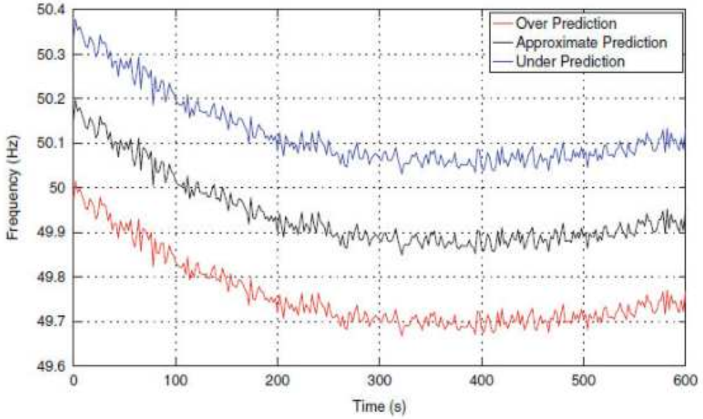
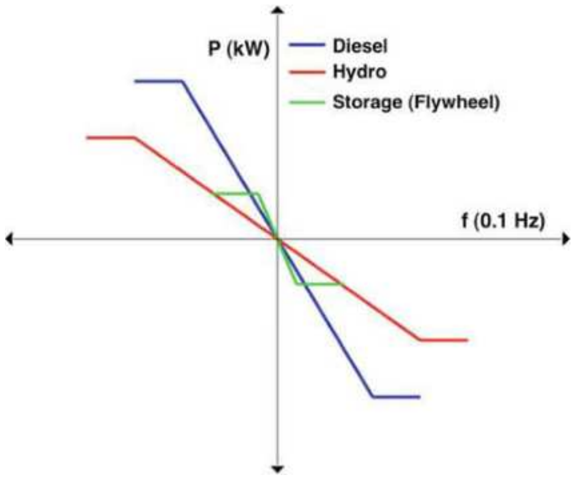


Fig. 14.3 Flores: persistent frequency deviations in the system



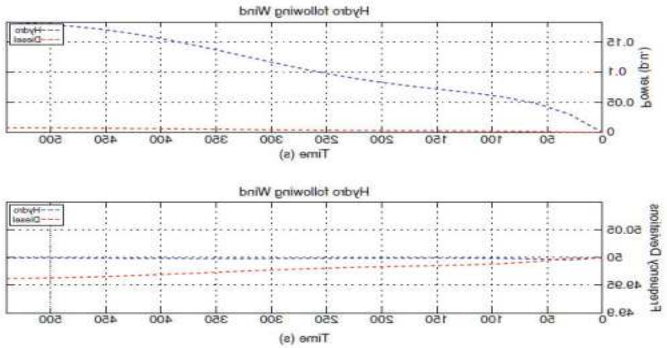


Fig. 14.9 Hydro unit balancing intra-dispatch wind variations

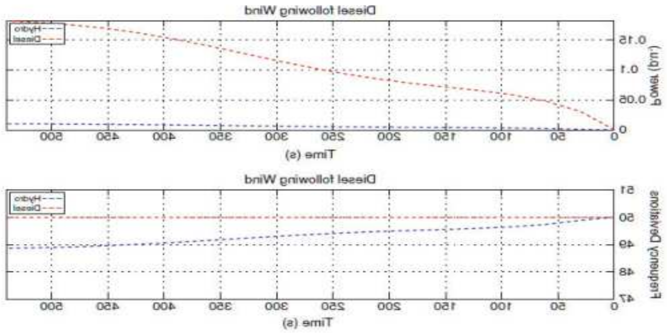


Fig. 14.10 Diesel unit balancing intra-dispatch wind variations

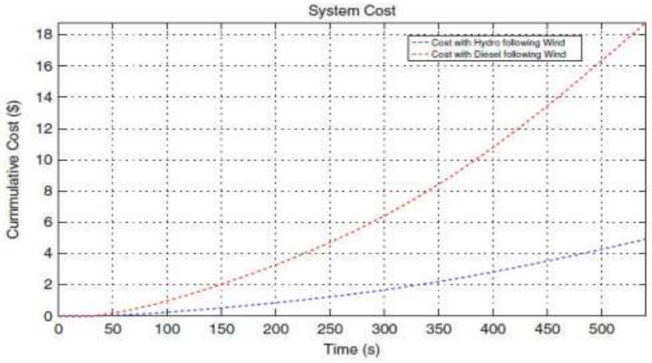
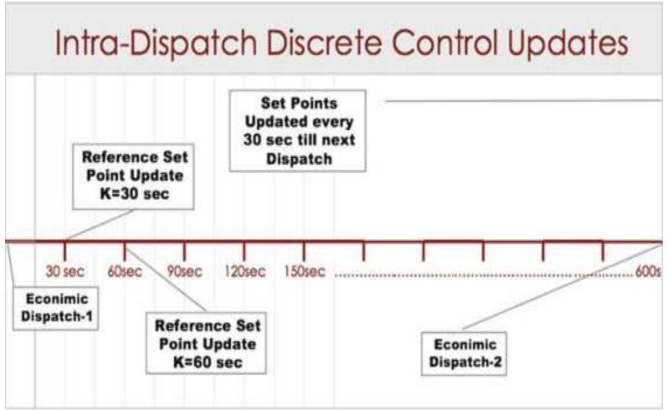


Fig. 14.14 Comparing cumulative cost over 10 min



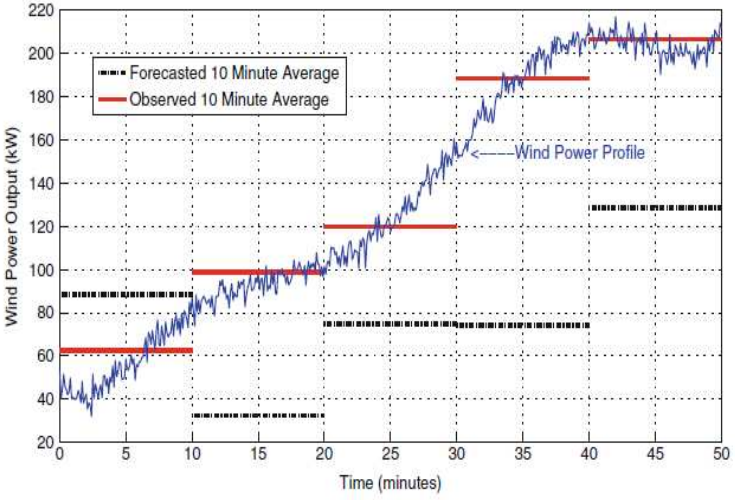


Fig. 14.1 10-Min ahead wind power forecast and actual wind power output

How to make it robust/small-signal stable?

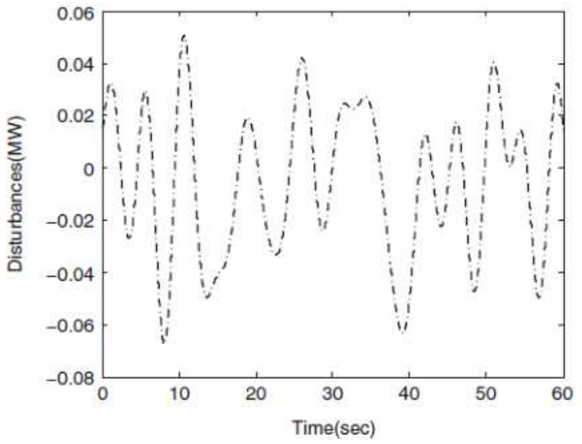


Fig. 15.7 Wind power disturbances under current penetration level

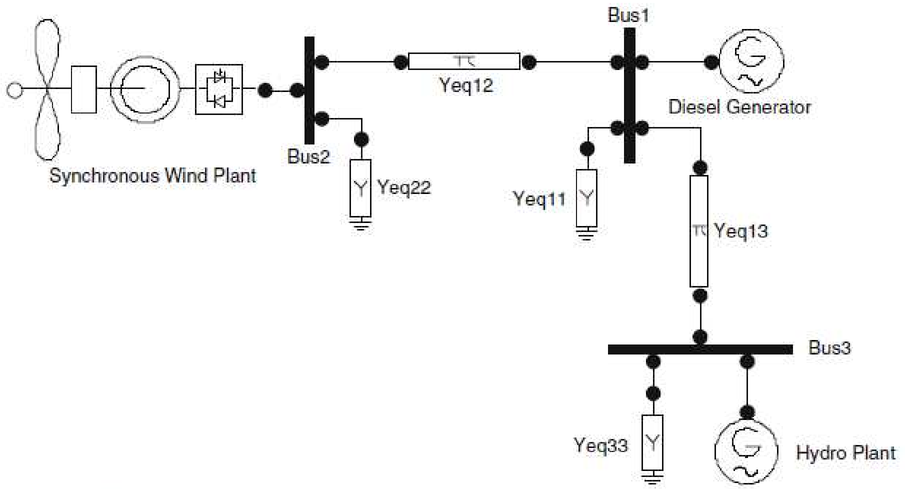


Table 15.1 Eigenvalues of the dynamic components

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

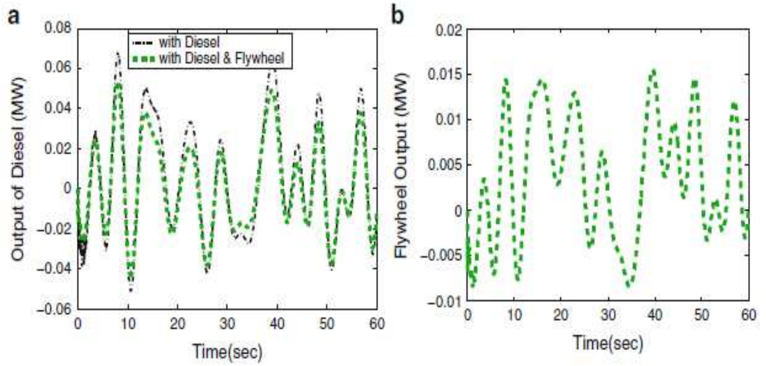


Fig. 15.9 Output of diesel and flywheel in response to frequency deviations, Case 1: system with synchronous wind generator. (a) Output of diesel generator. (b) Output of flywheel

Table 15.4 Eigenvalues of the dynamic components

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

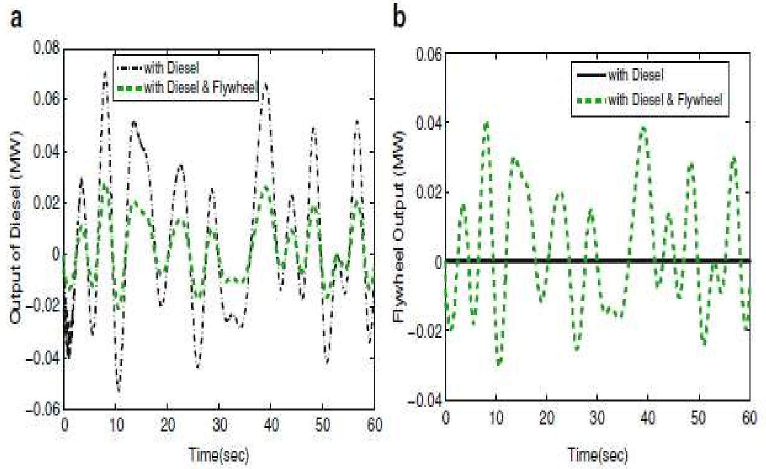
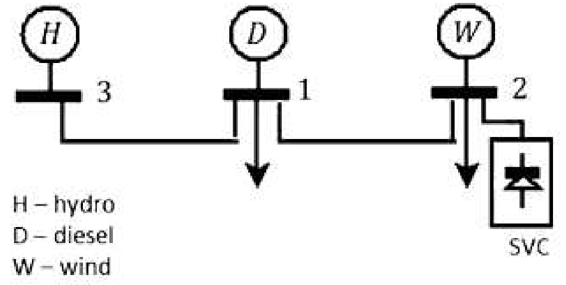


Fig. 15.11 Output of diesel and flywheel in response to frequency deviations, Case 2: system with negative load wind generator. (a) Output of diesel generator. (b) Output of flywheel

Transient stabilization in systems with wind power –SVC

Potential of Nonlinear Fast Power-Electronically-Switched Storage



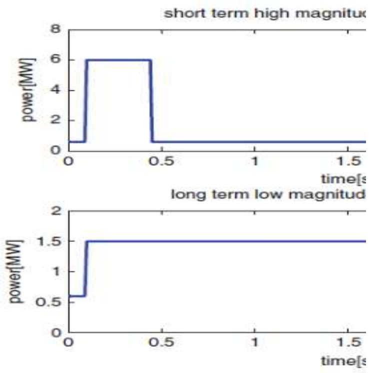


Fig. 19.2 Wind disturbances simulated in the Flores e

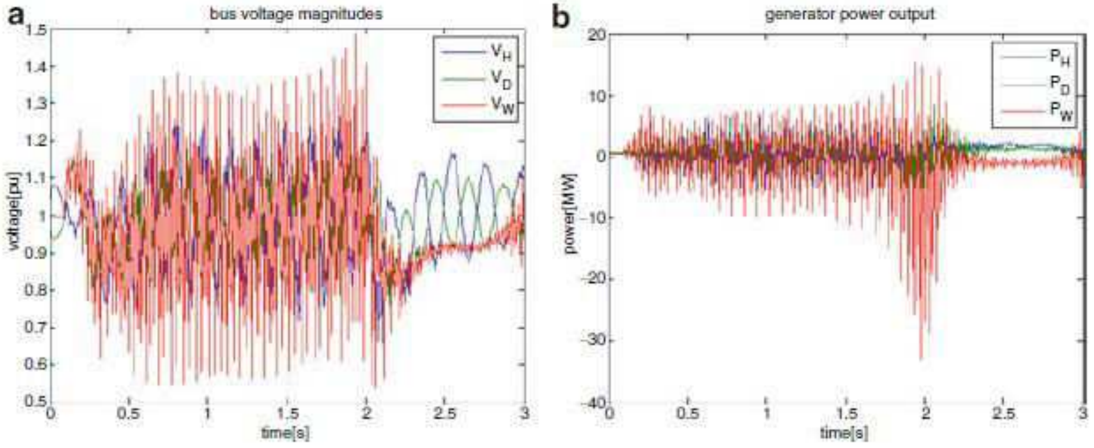


Fig. 19.14 (a) Voltage on the buses and (b) the electric power output of the generators if the system is controlled by the proposed energy-based controller

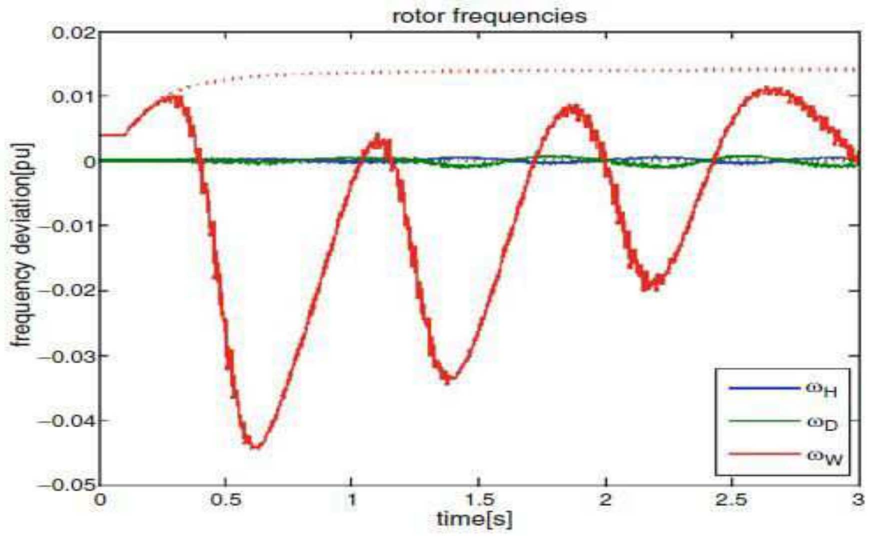


Fig. 19.16 Mechanical frequency of all generators in the system during a long-term low-magnitude wind perturbation: (a) *dashed* (without control on the SVC), (b) *solid* (with control on the SVC)

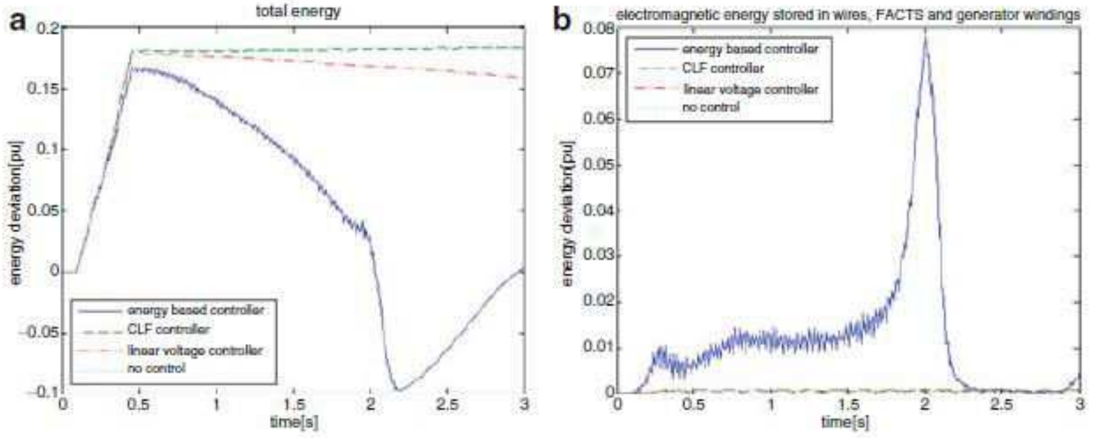
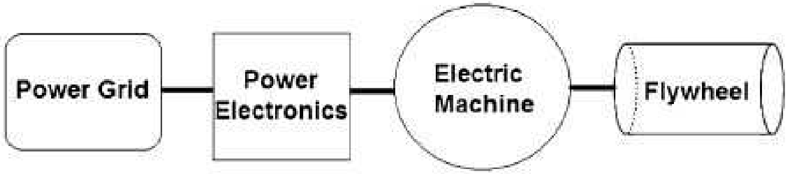


Fig. 19.15 (a) Total accumulated energy and (b) total accumulated electromagnetic energy in a system controlled by different controllers

Transient stabilization using flywheels

Concept of Sliding Mode Control Applied to a Flywheel



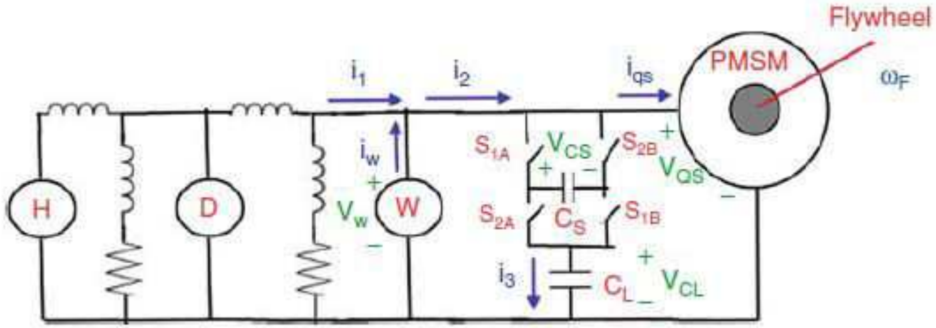


Fig. 19.34 Full diagram connecting the flywheel to Flores

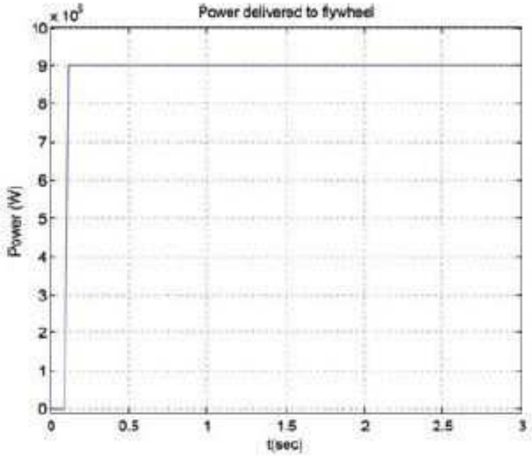


Fig. 19.32 Power delivered to the flywheel in r

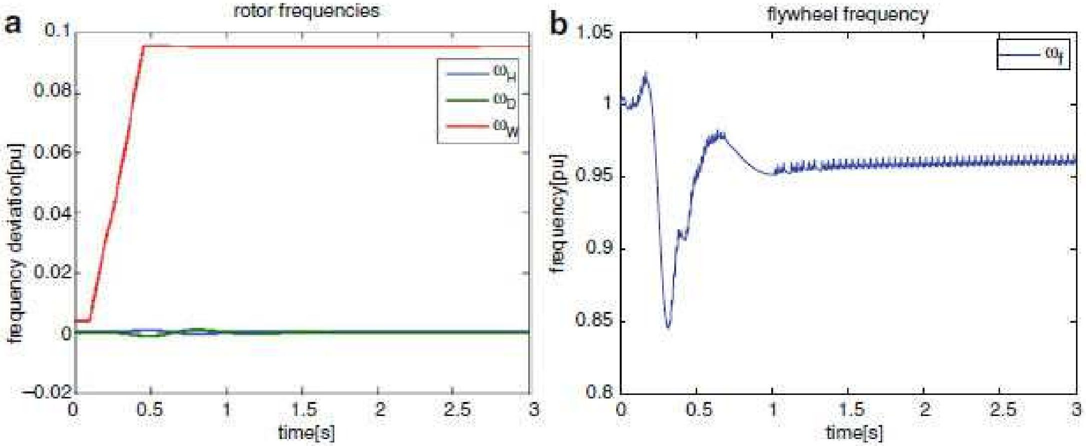
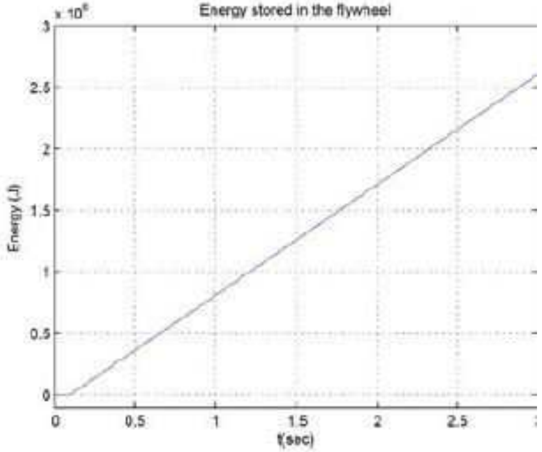


Fig. 19.35 Frequency of (a) the hydro, diesel, and wind generators, and (b) the flywheel, in the Flores system



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

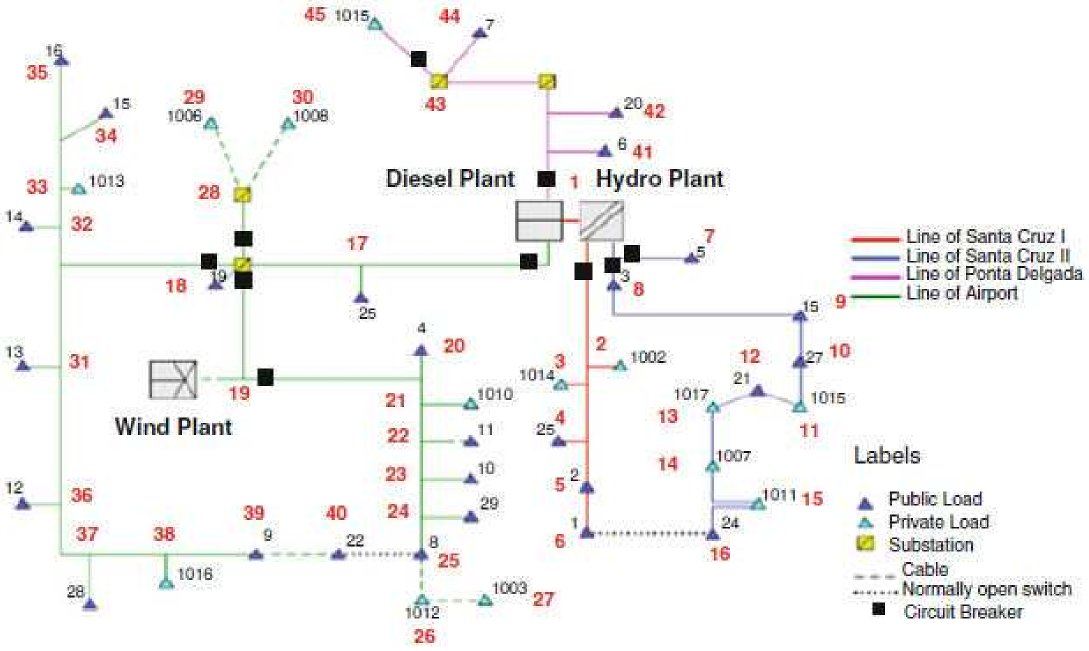


Fig. 18.1 The distribution system on the island of Flores

Toward Reconfigurable Smart Distribution Systems for Differentiated Reliability of Service

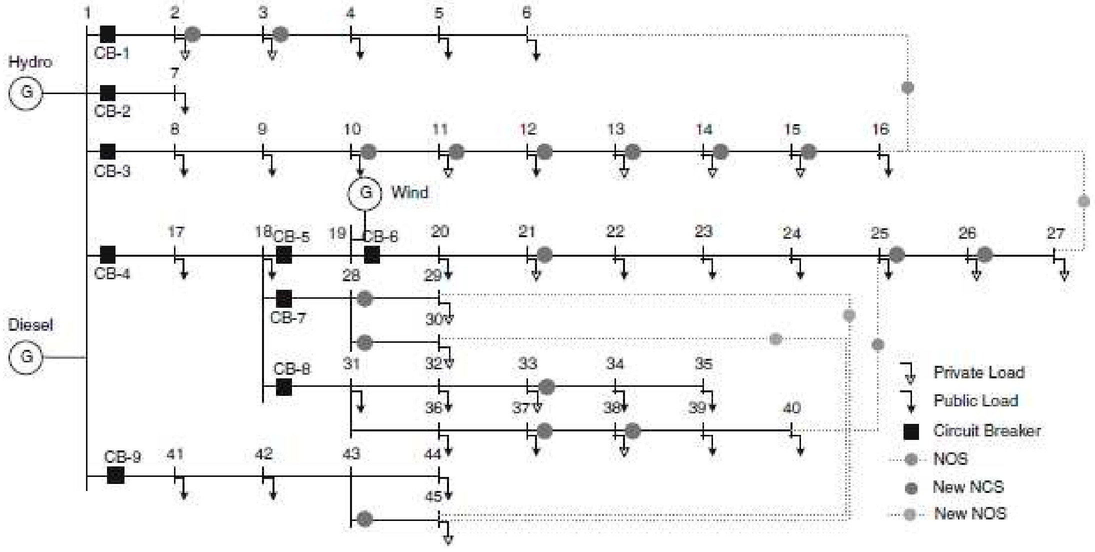
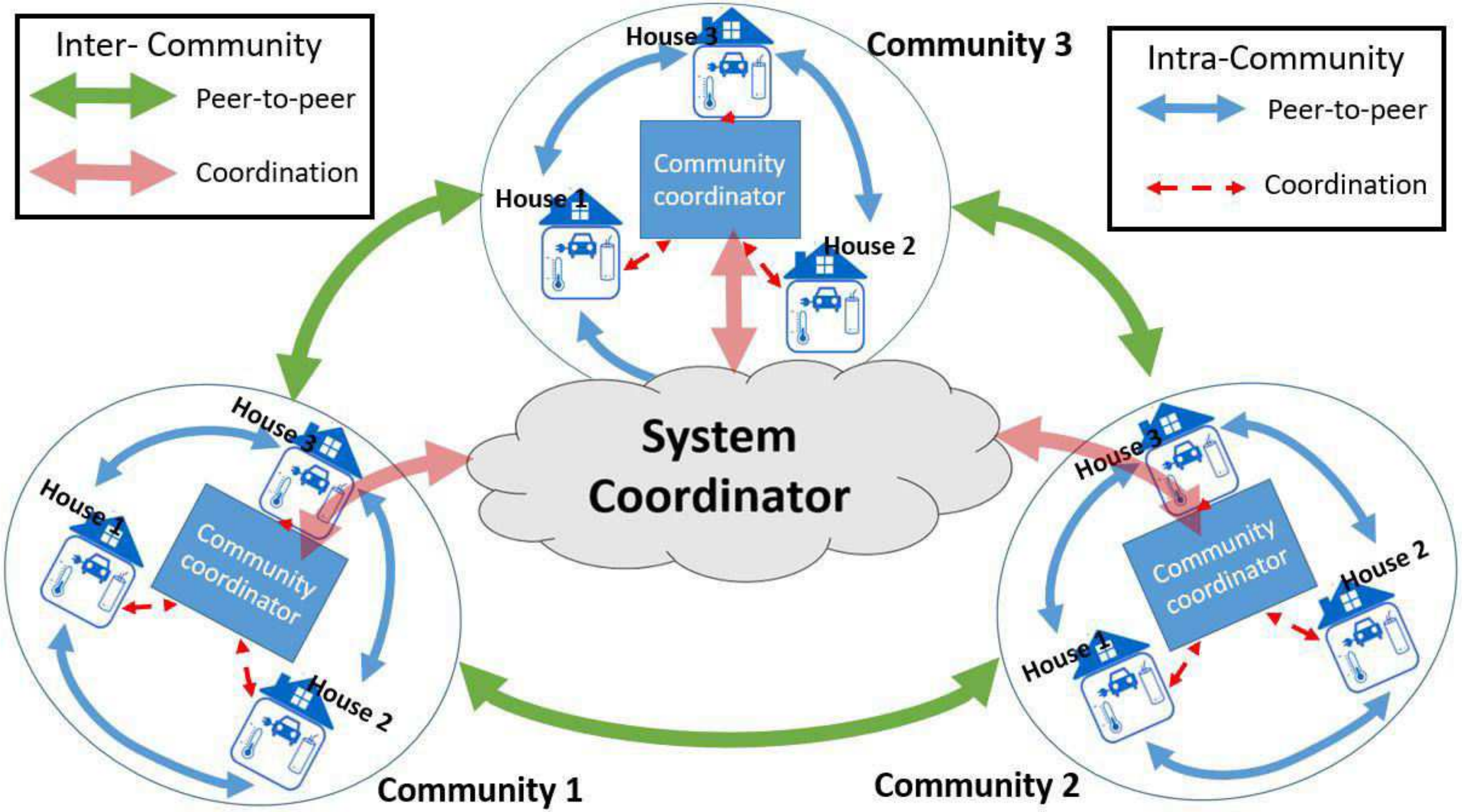


Fig. 18.4 The locations to install NCSs and NOSs

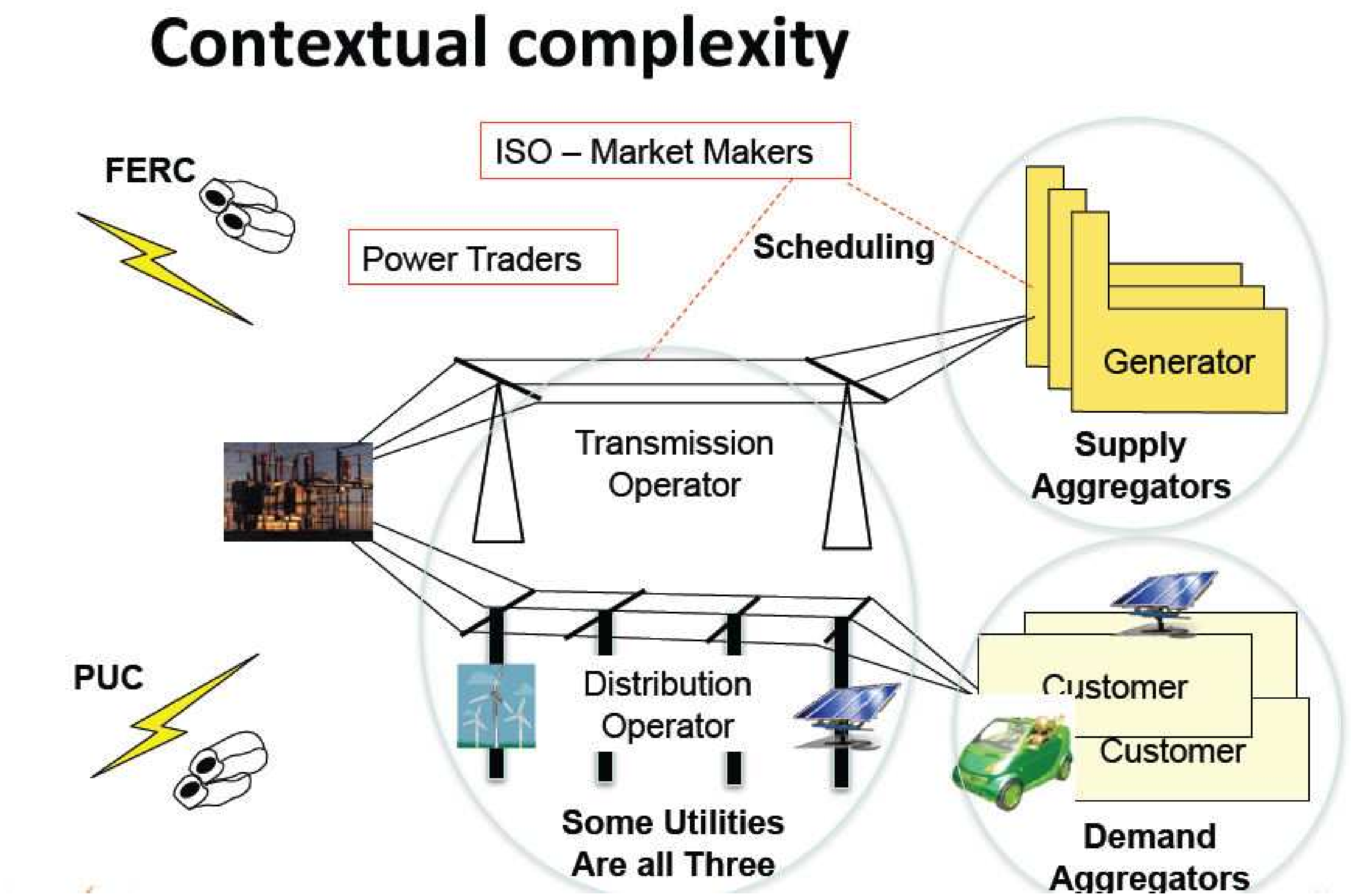
Table 18.1 Comparison of total costs between the original and modified system

	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

Smart communities

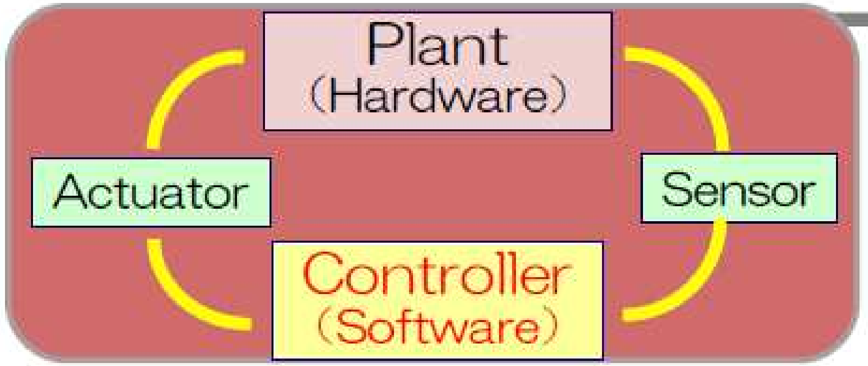


Today's operations technology (OT) and information technology (IT)



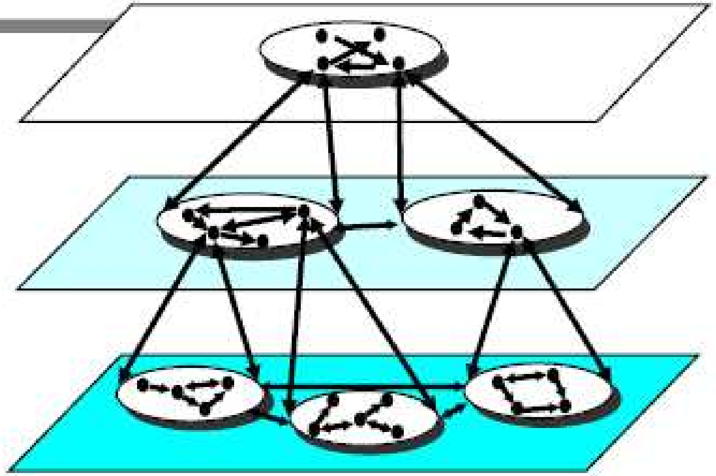
Next generation IT/OT for energy systems(Japan)

① Feedback



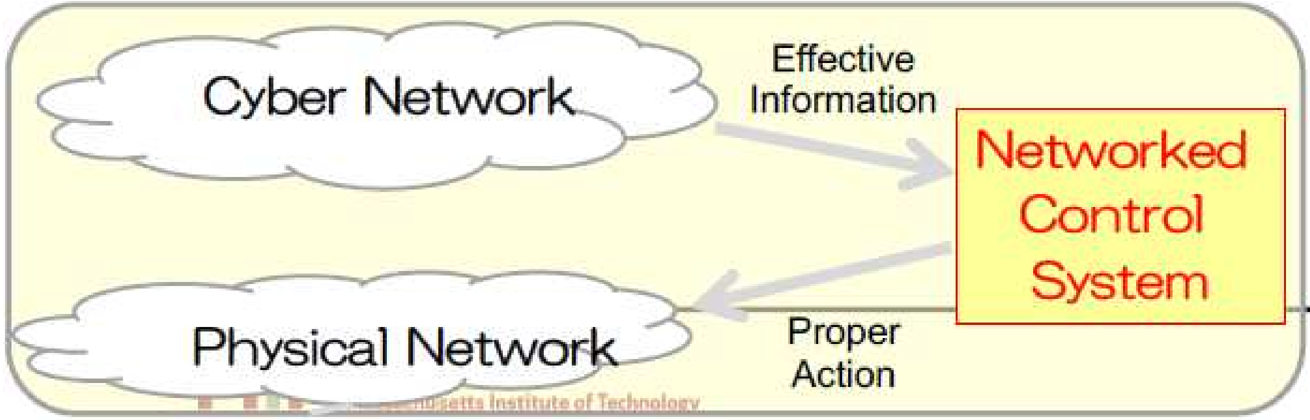
Feedback System

③ Hierarchy (SoS)



Interactive iBAs

② Hybrid (CPNS)



Cyber Physical Network System

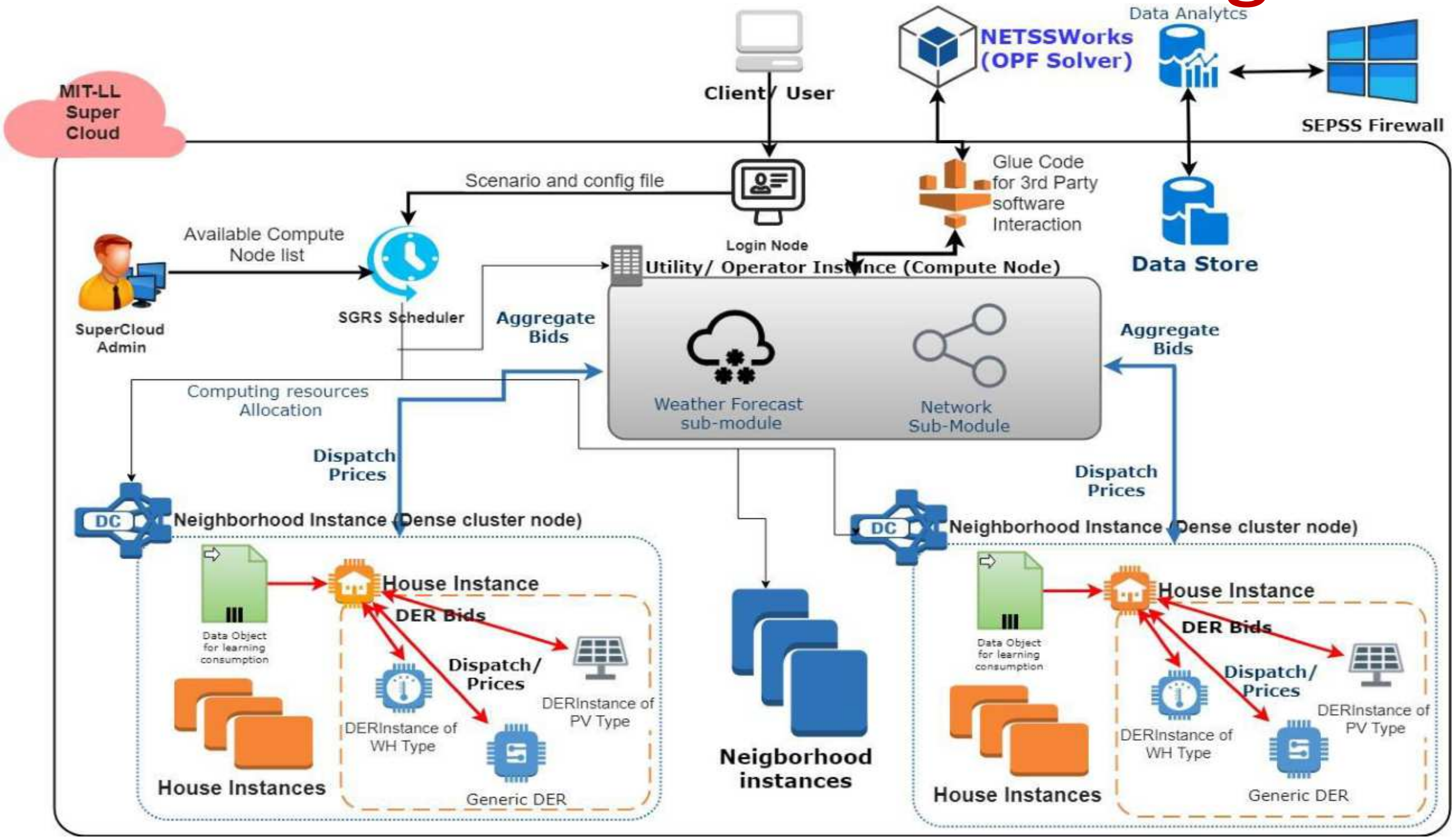
S. Hara & S. Honda, "System Science and Technology for Super Smart Society", Keisoku to Seigyo (Measurement and Control), Vol. 55, no. 4, pp. 284-287, 2016 , (in Japanese)

Scalable Electric Power System Simulator (SEPSS) evolving into Dynamic Monitoring and Decision Systems (DyMonDS) Digital Twin

- Over the past > 10 years, SEPSS has been used to simulate both stochastic and deterministic Adaptive Load management (ALM).
- More recently, SGRS-enabled SEPSS was used in collaboration with MIT-LL to simulate microgrids and their participation in transactive energy markets (TEM).
- Recent particular use of SEPSS has been in collaboration with Pecan Street, Inc under ARPA-E project on synthetic regulating reserves (SRRs) by DERs. This can be thought of as an example of TEM supporting ancillary services provision.
- We have also shown fundamental need for voltage dispatch market signals to ensure reliable operation.
- We have shown in collaboration with MIT-LL potential benefits from advanced power inverter control for enabling reliable integration of PVs and EVs.

The most unique feature of our framework is its fundamental architecture modeled as complex interactive dynamical system.

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

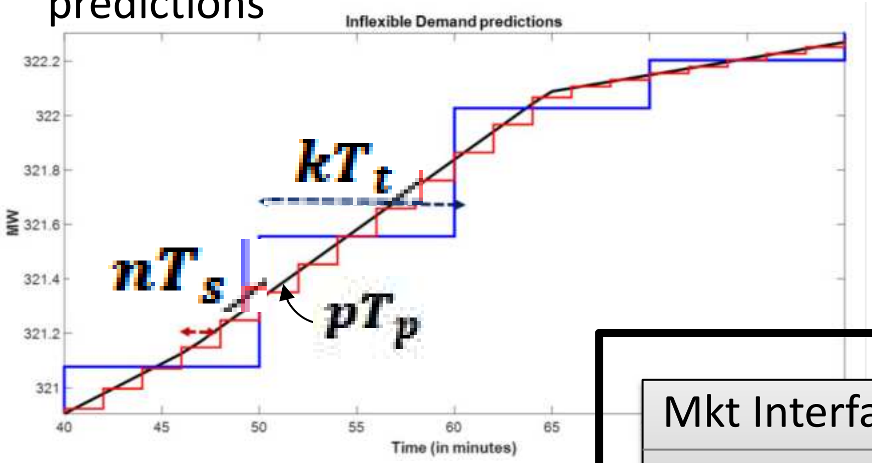
- Third party software (NETSSWorks) integrated to exploit its voltage optimization capability in its OPF problem
- SGRS scheduler utilized to initiate the simulation, eliminating the need for having a co-simulation master program

**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).*

Communication Framework-Dependent Economic and Physical Outcomes

Problem Posing:

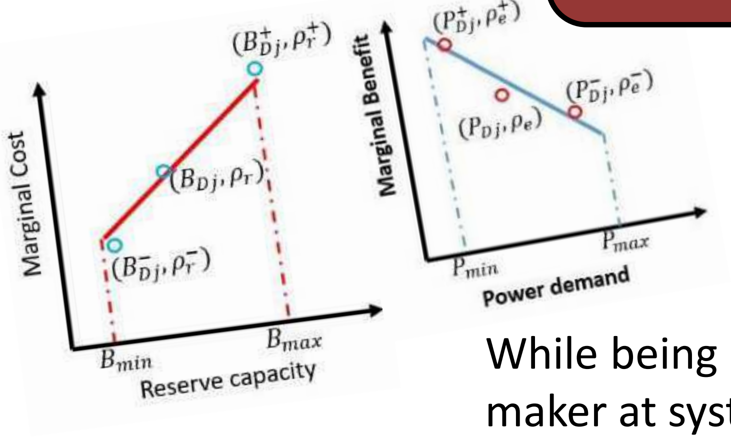
Given NODES Level inflexible demand predictions



Energy and Reserve Capacity bids $[k]$

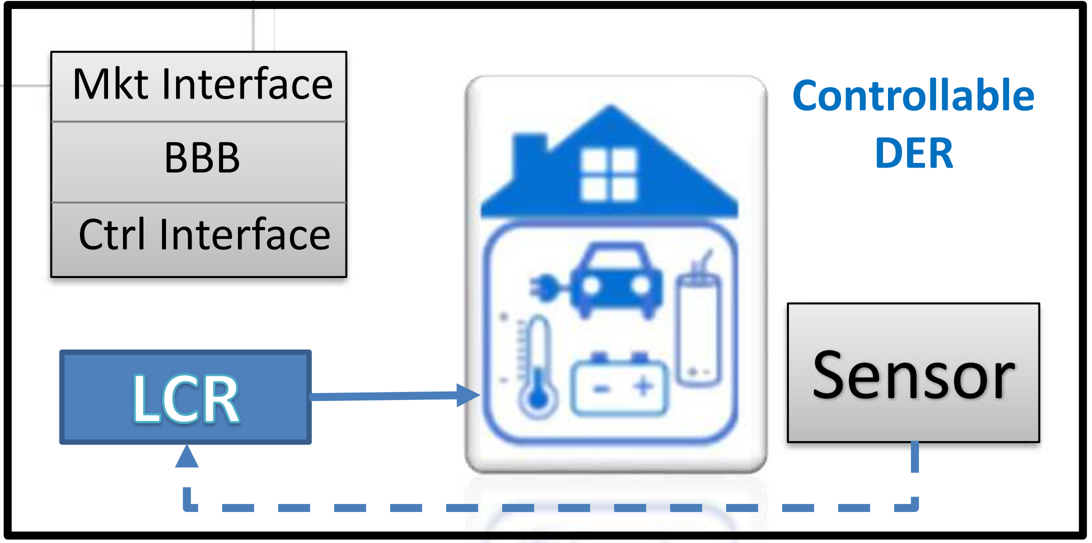
ISO

NODES



While being a price maker at system level

Coordinate controllable DERs and acquire sufficient reserves



To meet performance specifications on SRRs

Communication Framework-Dependent Economic and Physical Outcomes

Approach 1:

NODES as a Master Controller

Complex optimization solved through ***MINLP*** or queuing theory based

Simplifications:

- Relaxation
- Empirical DER models and approximations

Most Common Approach

ISO

NODES

Tertiary Control
Binary signal $[p]$

Measurements $[p]$

Mkt Interface
BBB
Ctrl Interface

LCR

Control
$[p]$

Controllable DER

Sensor

Measurements $[p]$

Implications (Technical):

- SRR may not be guaranteed
- DER may not be able to implement

Implications (Economic):

- NODES – Price Maker
- DER- Price Taker

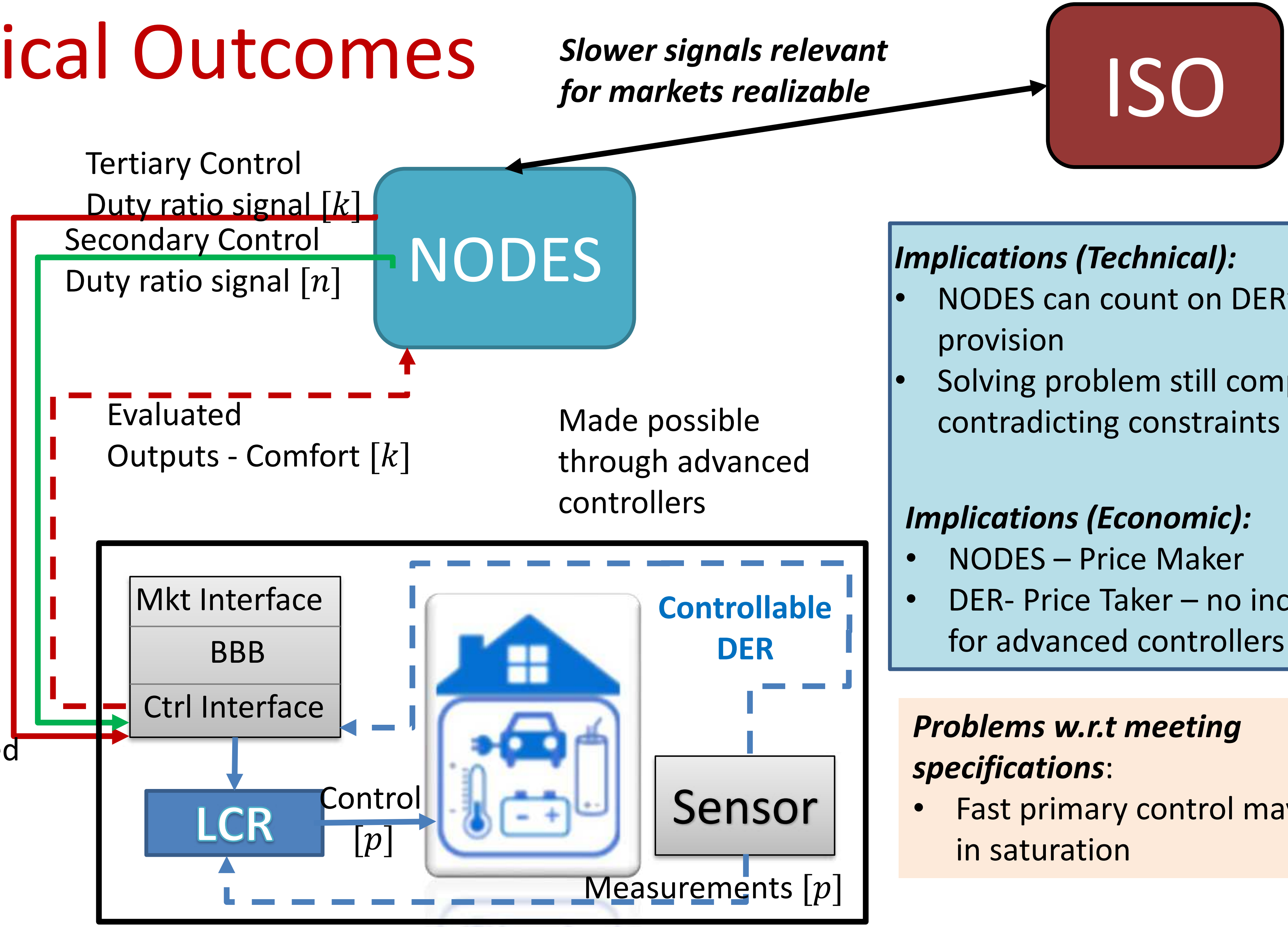
Issues w.r.t meeting specifications:

- Fastest time scale platform implementations
- Complex problem at NODES

Communication Framework-Dependent Economic and Physical Outcomes

Approach 2:

NODES as a master Controller with DER physics internalized



Fast sensor measurements utilized to compensate non-linearities

Implications (Technical):

- NODES can count on DER's SRR provision
- Solving problem still complex – contradicting constraints

Implications (Economic):

- NODES – Price Maker
- DER- Price Taker – no incentive for advanced controllers

***Problems w.r.t meeting specifications*:**

- Fast primary control may result in saturation

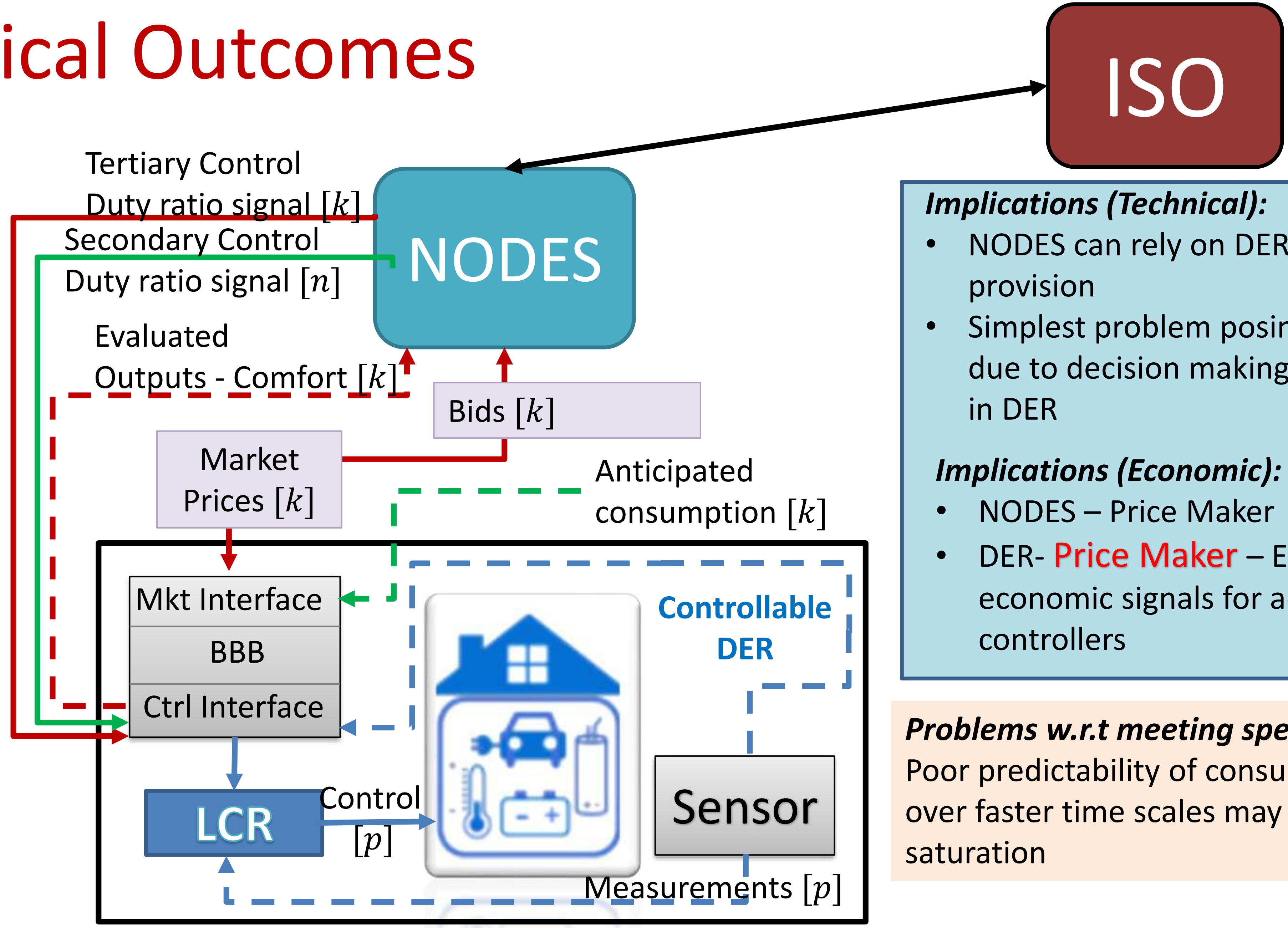
Communication Framework-Dependent Economic and Physical Outcomes

Approach 3:

DyMonDS-
NODES and DER distributed decision makers

Market Interface of BBB now is involved in DER decision making

Slower signals relevant for markets realizable



Implications (Technical):

- NODES can rely on DER's SRR provision
- Simplest problem posing at NODES due to decision making embedded in DER

Implications (Economic):

- NODES – Price Maker
- DER- Price Maker – Explicit economic signals for advanced controllers

Problems w.r.t meeting specifications:
Poor predictability of consumptions over faster time scales may cause saturation

Different SRR Implementation Platforms:

Impact on Meeting Performance Specifications

Approach	Economic	Technical
1	Price Taker	Not realizable
2	Price Taker	Claiming/ not claiming feasibility
3	Price Maker	Claiming feasibility

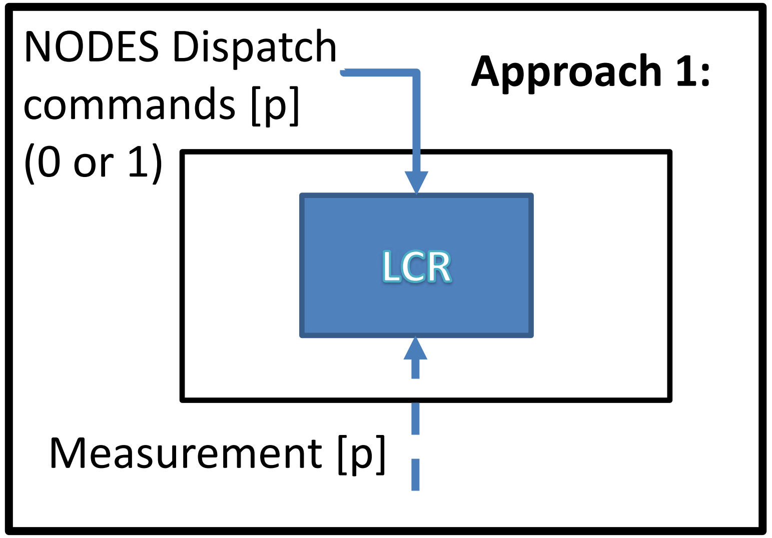
- DER-specific knowledge and its decisions are critical
- Internalizing fast dynamics at component level is important
- DERs' opting out explicitly at value in ***Approach 3 (Inelastic load)***
- **DyMonDS-based Scalable Electric Power System Simulator (SEPSS) – MIT general cloud platform**

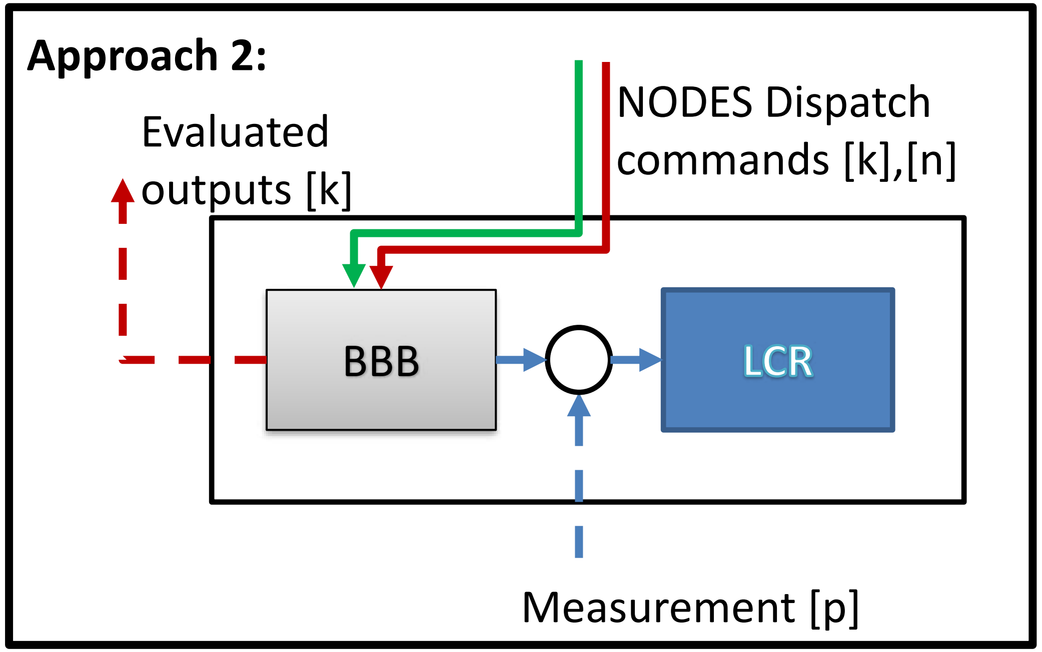
Composite Component Control

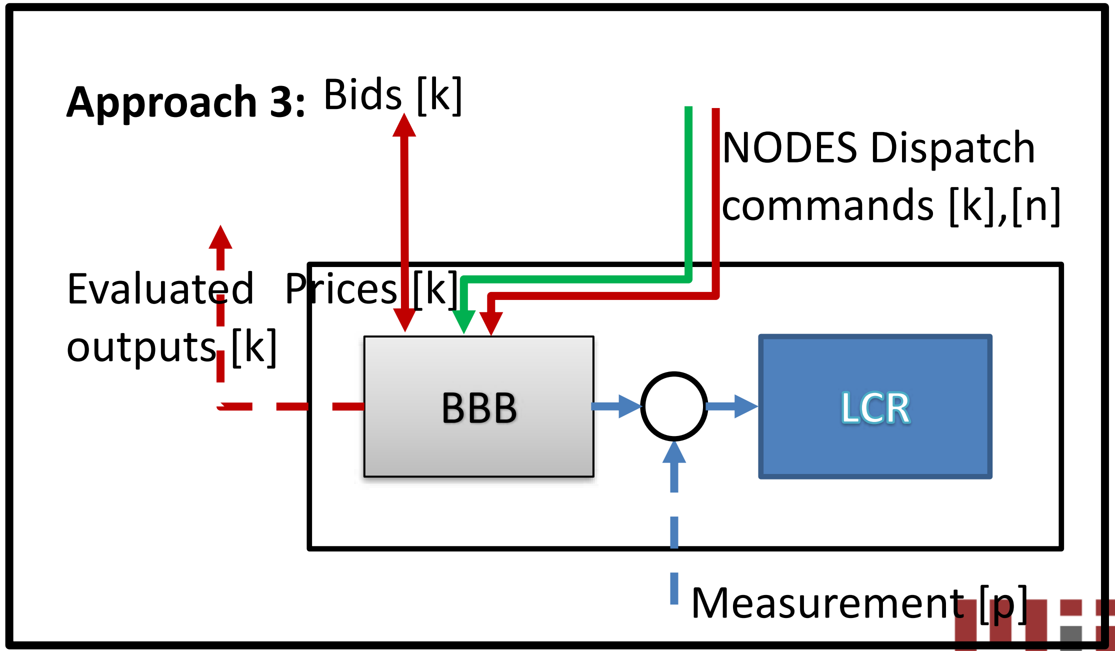
$$u[p] = u_{CC}[p] + u_{SRR}[n] + u_{EM}[k]$$
$$s.t.\ \ u_{min} \leq u[p] \leq u_{max}$$

DER functional objectives

- Consumer comfort $[p]$
- SRR signal implement ability $[n]$
- Energy Market and SRR capacity market participation $[k]$

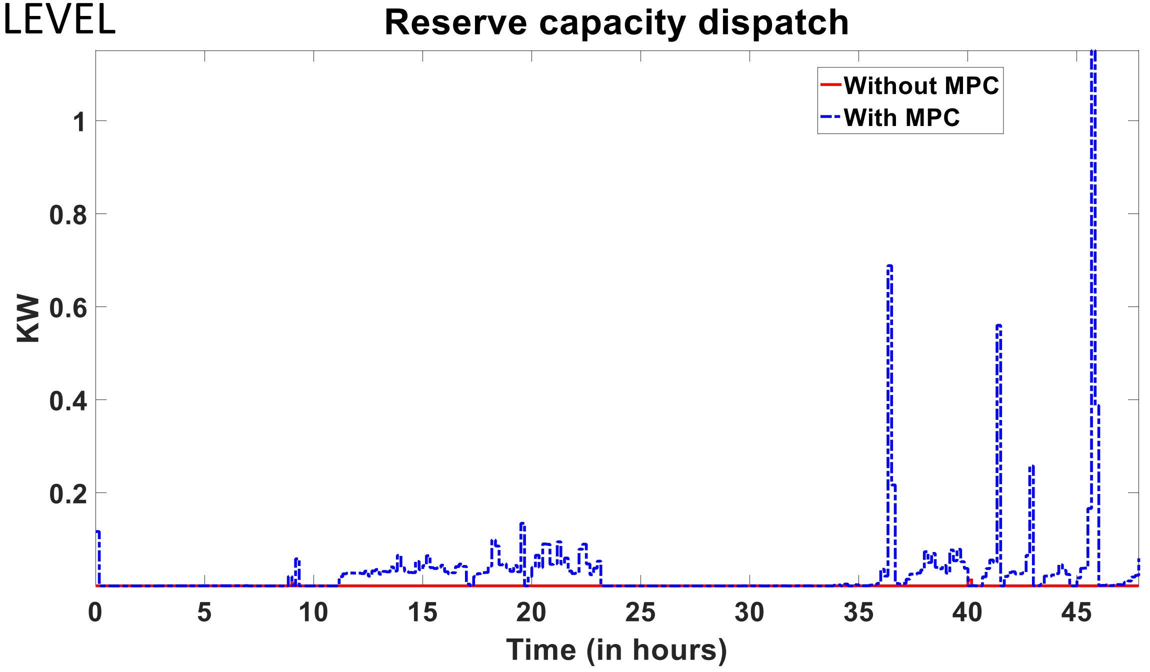


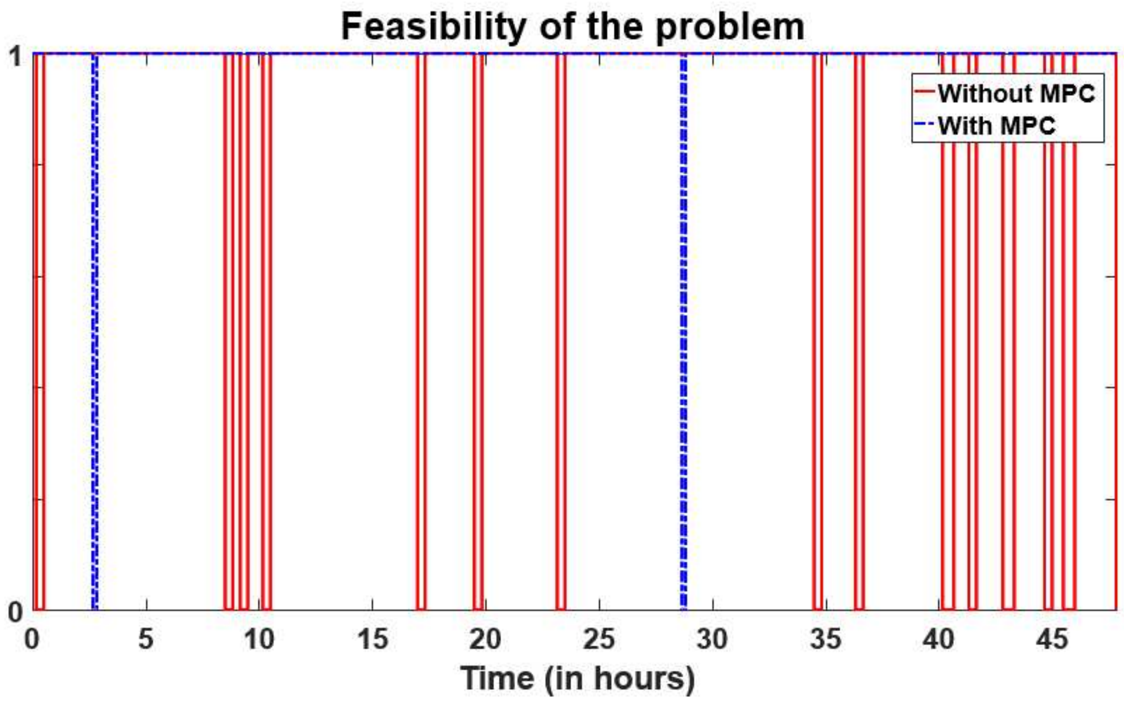




Lessons learned by using Pecan street data

COMPONENT LEVEL



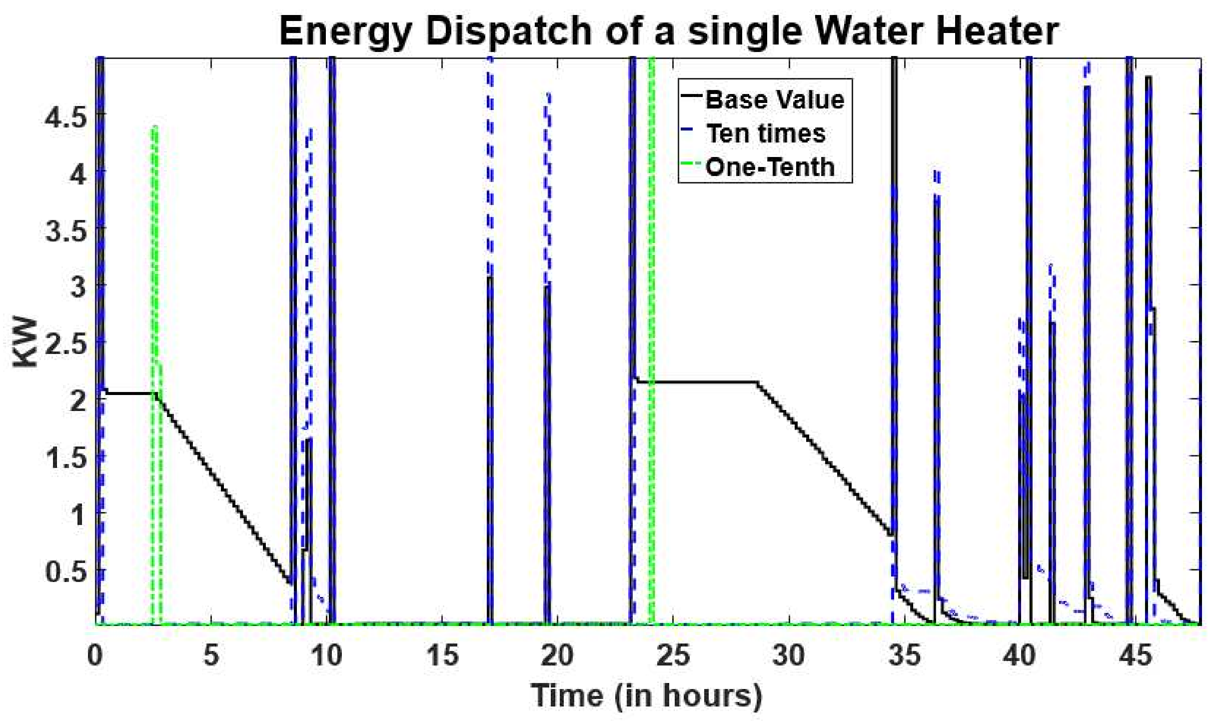


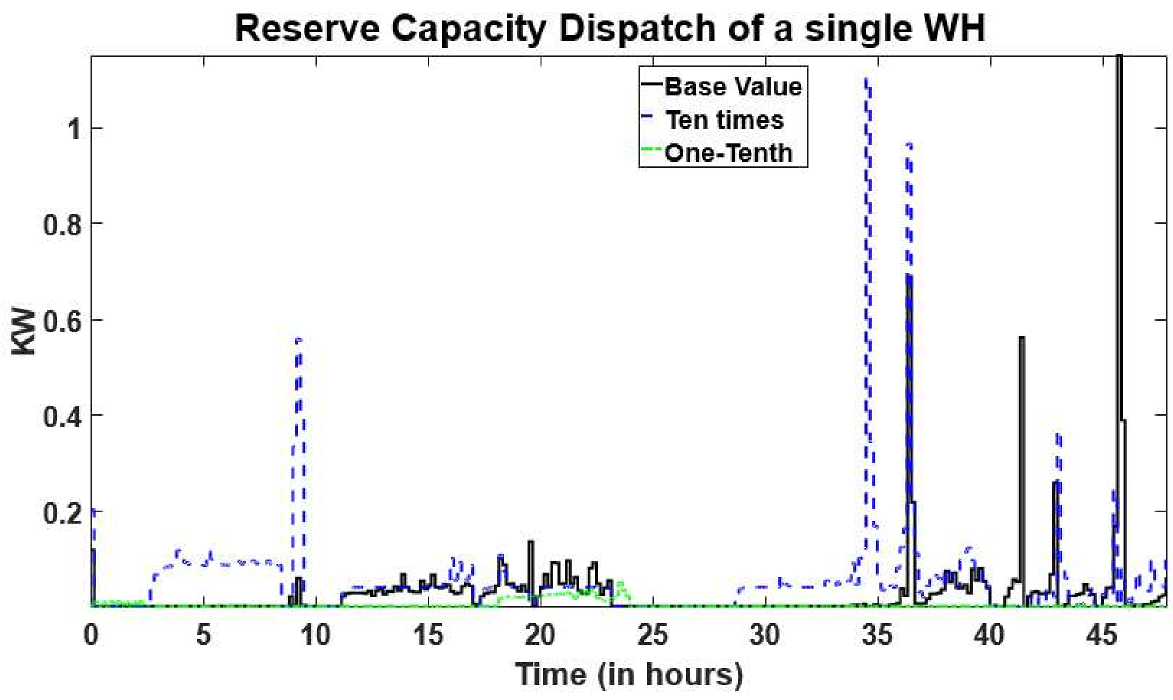
Longer planning periods of MPC results in larger reserve capacity scheduling

Lesser probability of infeasibility with MPC

- **Key-role of Model Predictive Control (MPC)**

Lessons learned by using Pecan street data

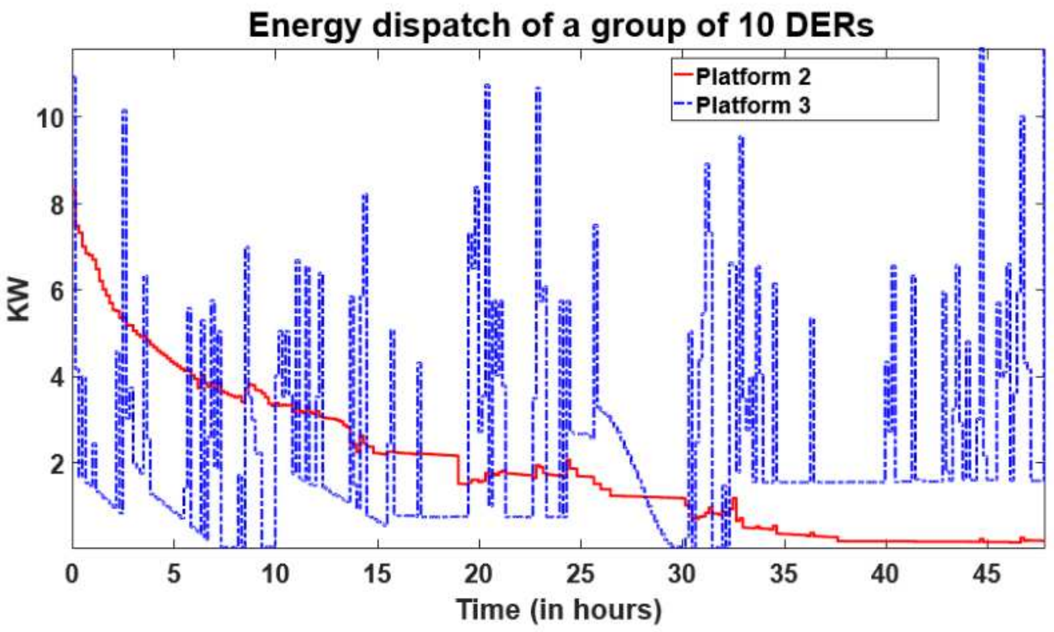


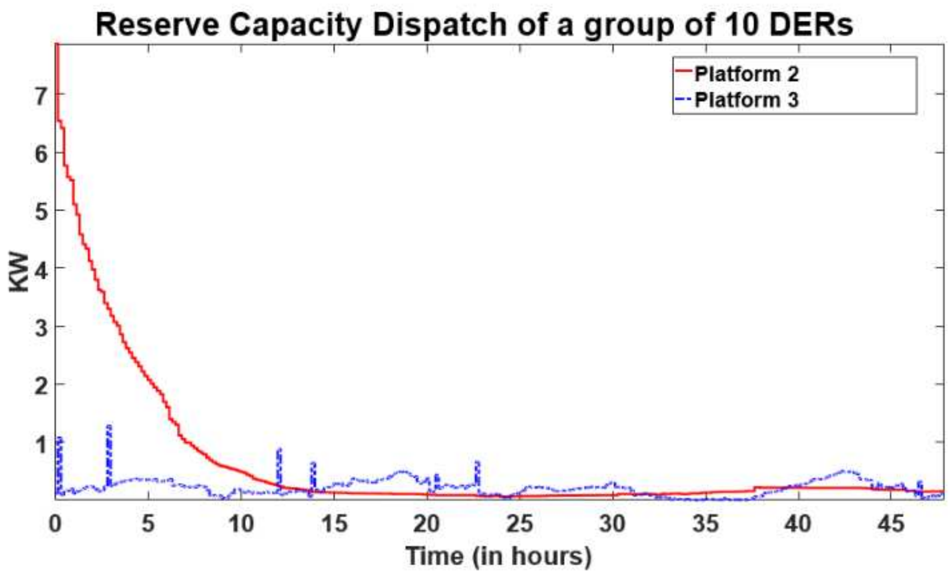


Higher the reserve price, more frequently DER consumes energy, to be able to participate in reserve capacity

- Key-role of Model Predictive Control (MPC)
- **Effect of relative reserve price**

Lessons learned by using Pecan street data





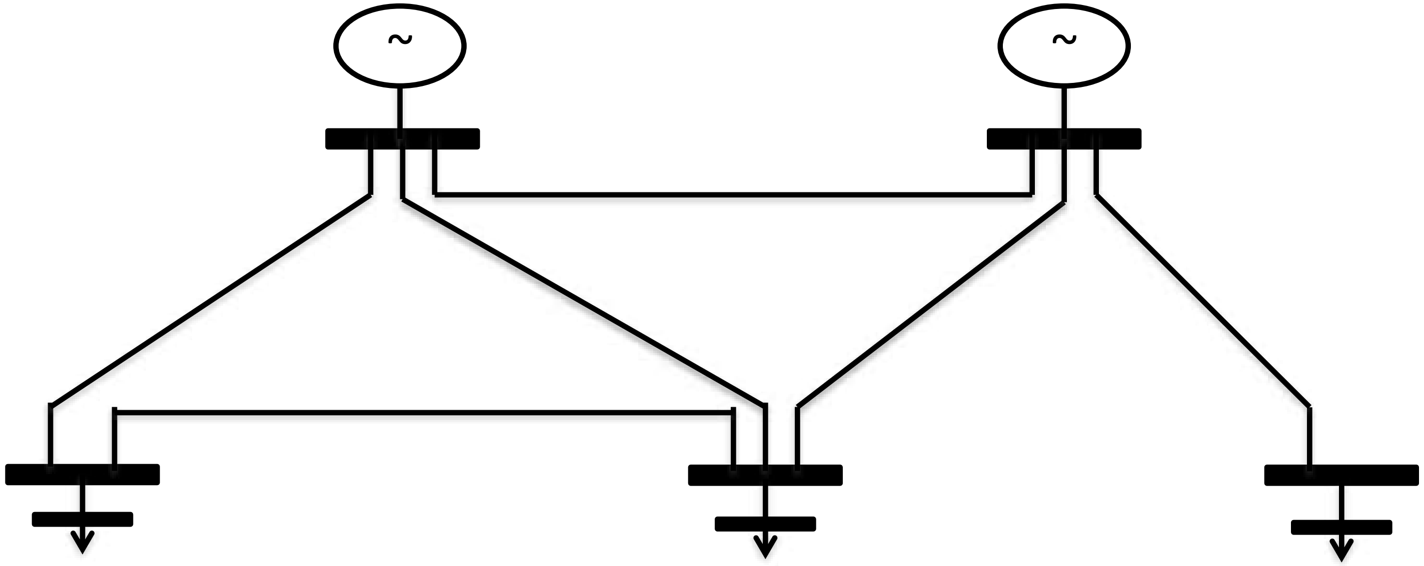
Aggregate level decision making can lead to infeasible DER command

- Key-role of MPC
- Effect of relative reserve price
- **Effect of platform design**

Basis for binding protocols in SRR platforms (2&3)

The Changing Landscape of Local (Distribution) Grids

- **Influx of small resources; sensors; controllers (including smart wires)**



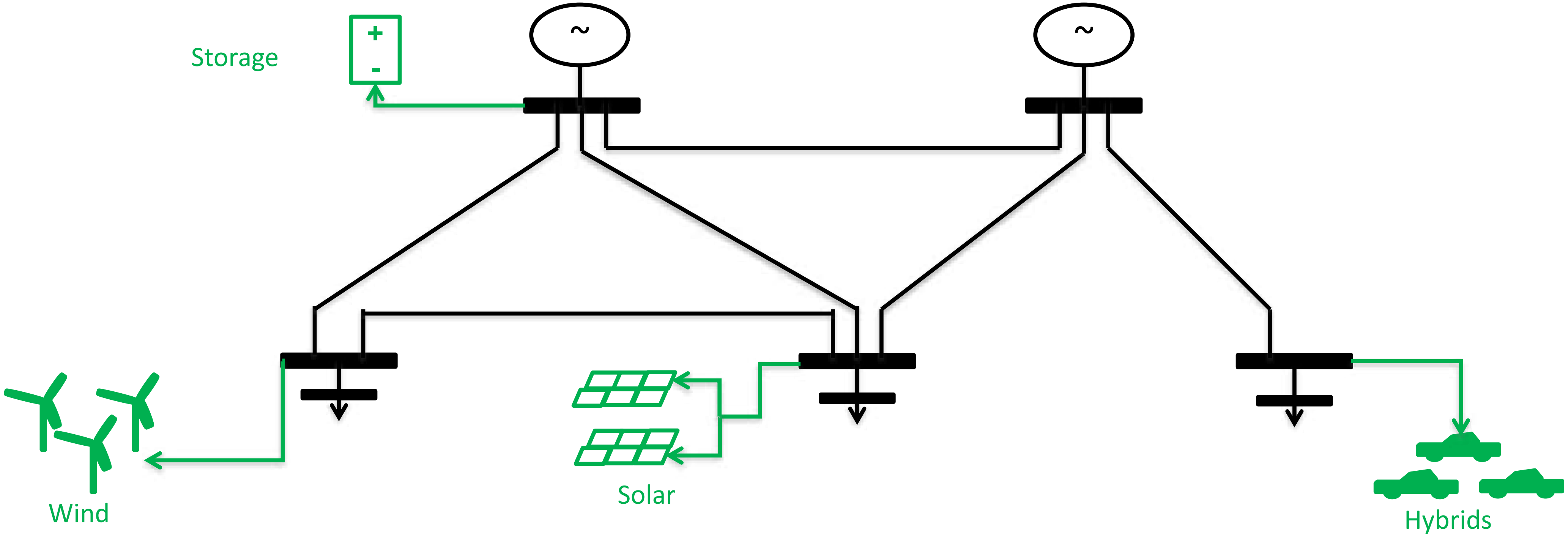
Typical Interconnected Electric Energy System

Ilic, M. D., & Hsu, A. (2012, January). Toward distributed contingency screening using line flow calculators and dynamic line rating units (DLRS). In *2012 45th Hawaii International Conference on System Sciences* (pp. 2027-2035). IEEE.

M.D. Ili´c and A. Hsu, "A General Method for Distributed Line Flow computing with Local Communication in Meshed Electric Networks: applications to Distributed Line Power Flow Calculations with Minimal Communications," US Patent No. 2013/0024168 A1, Jan. 2013.

The Changing Landscape of Electric Energy Systems

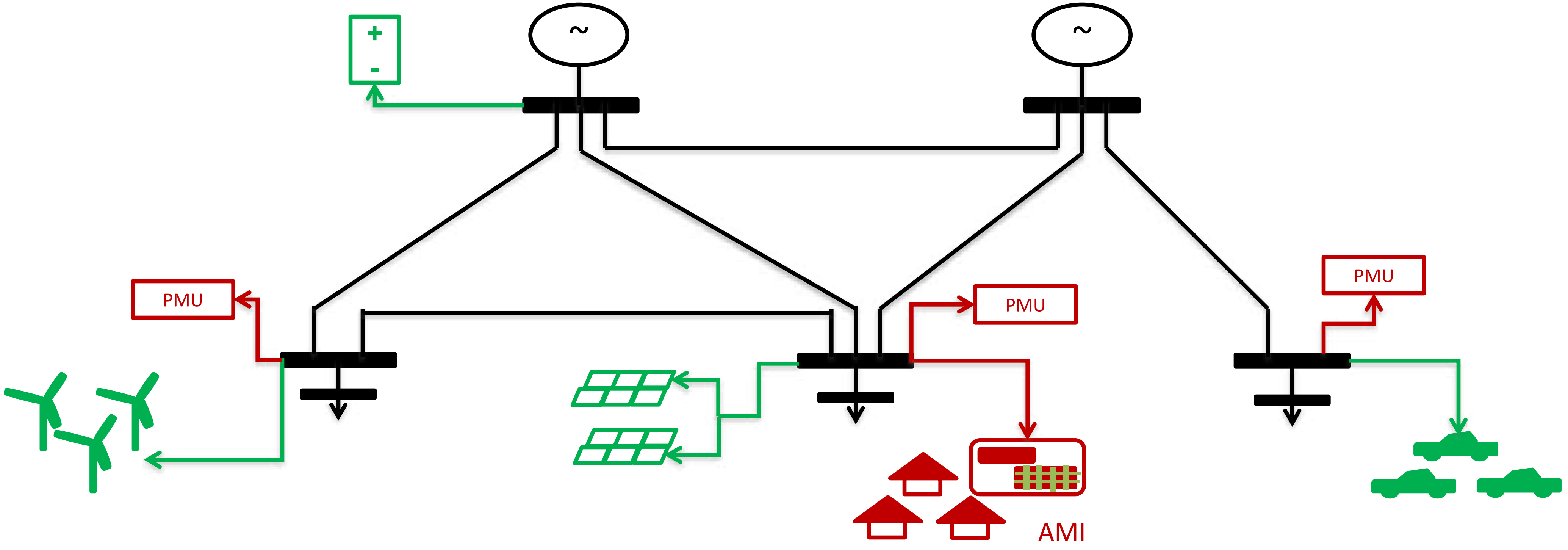
- Influx of small resources; sensors; controllers (including smart wires)



Future Interconnected Electric Energy System
With Distributed Technologies

The Changing Landscape of Electric Energy Systems

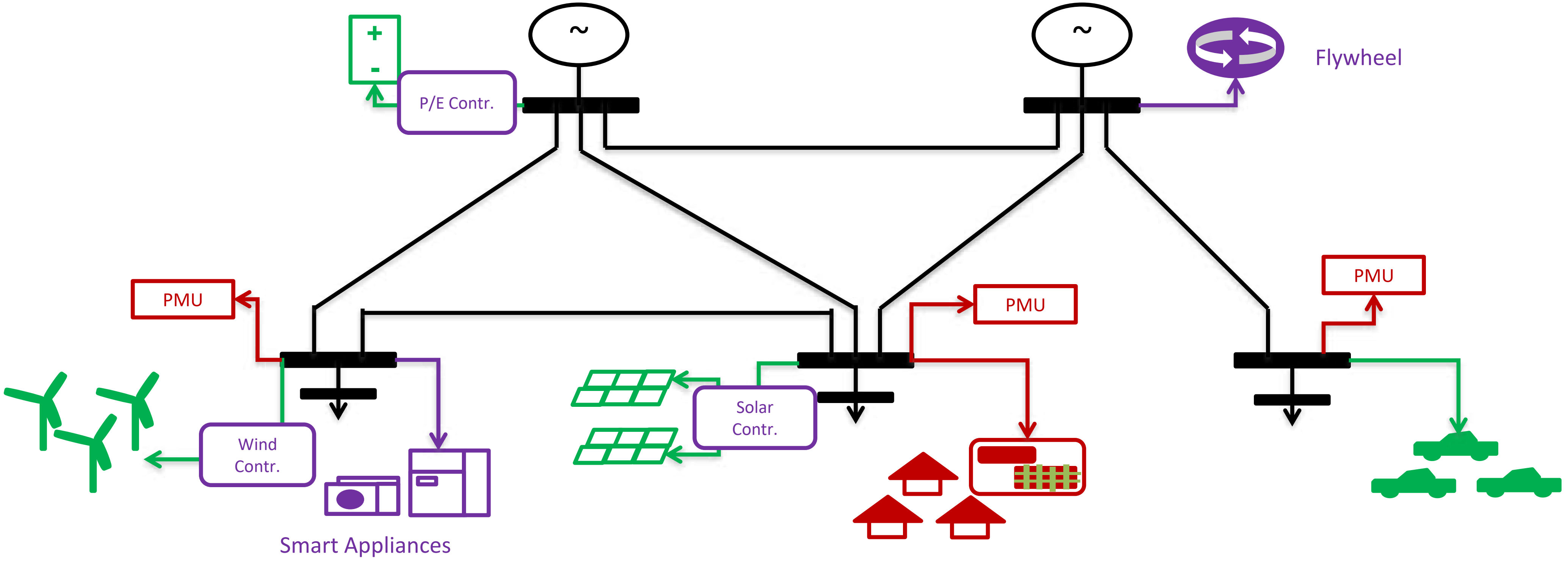
- Influx of small resources; sensors; controllers (including smart wires)



Distributed Sensors

The Changing Landscape of Electric Energy Systems

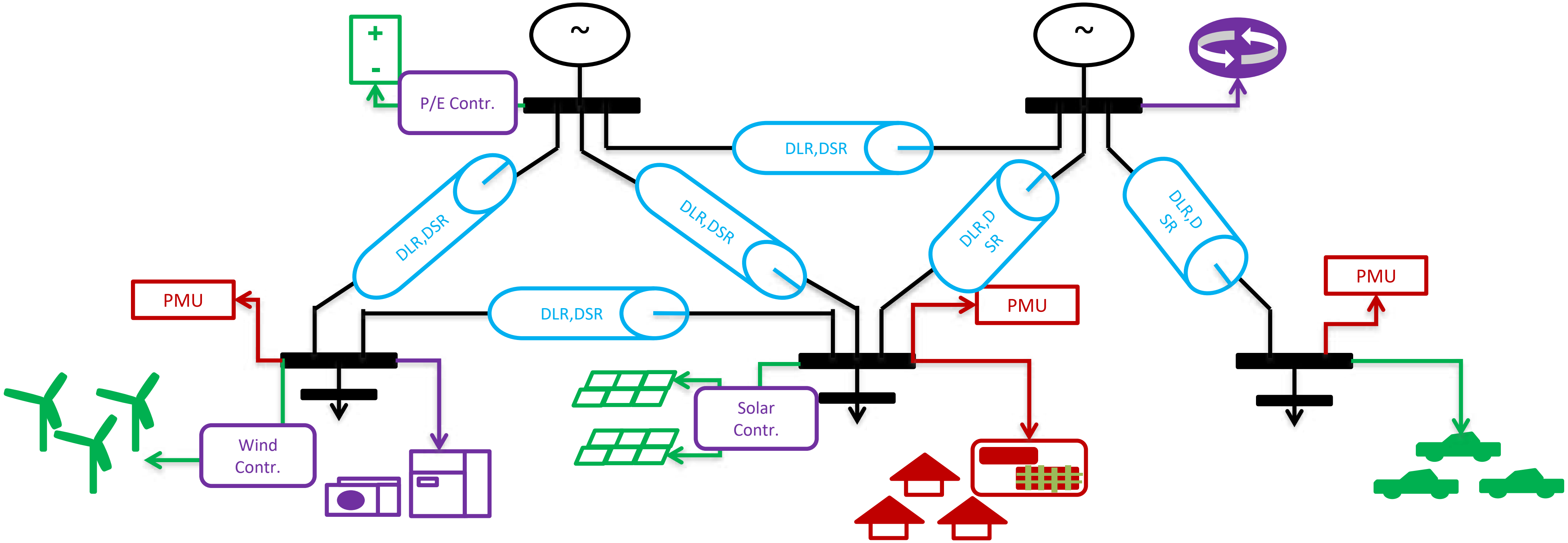
- Influx of small resources; sensors; controllers (including smart wires)



New Controllers And Devices

The Changing Landscape of Electric Energy Systems

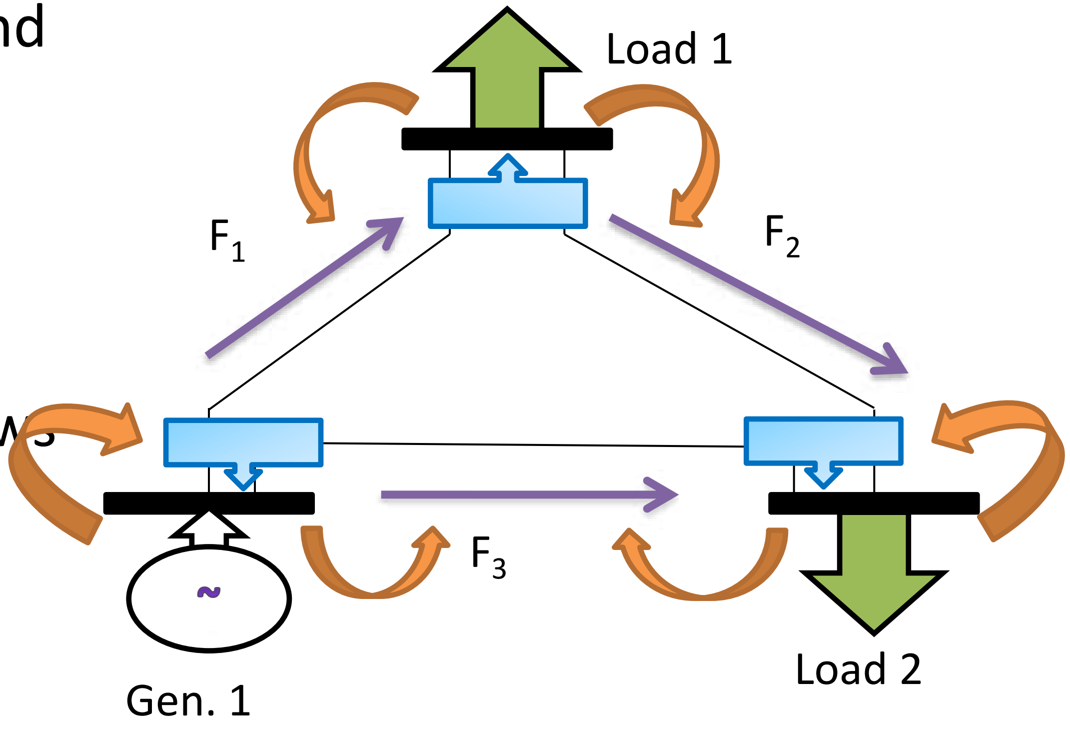
❖ **Influx of small resources; sensors; controllers (including smart wires)**



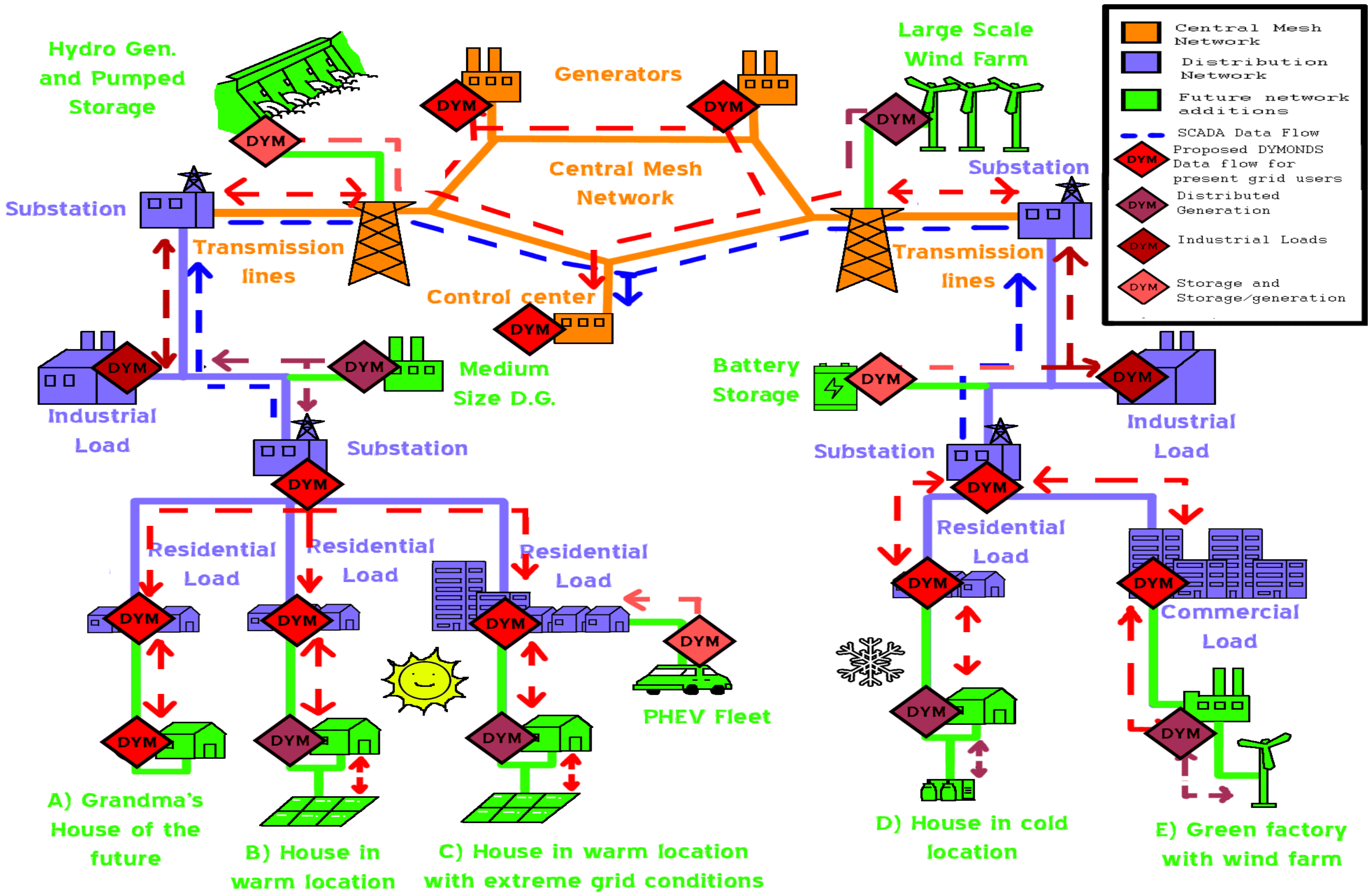
“Smart wires”, direct line flow sensors and controllers

Communications Requirements

- Lines and buses have their own calculators, and can communicate with directly connected branches
- The lines calculate their own flow variables based on voltages, and the buses calculate voltages and sensitivities for KCL based on flows from connected lines



NEXT GENERATION SCADA—
Dynamic Monitoring and Decision Systems (DyMonDS)



Opportunities

- **Pro-active use of on-line data for enhanced performance at value**

--Highly dynamic distributed complex networks with many decision makers

--Dynamic Monitoring and Decision Systems (DyMonDS) (Next generation SCADA)

- **Efficient supply-demand balancing and delivery in normal operation**

--From off-line worst case reserves to on-line data-enabled flexible utilization

--Interactive power balancing, incl. EVs; Key role of data-enabled delivery (grid control)

- **Efficient management of uncertainties in extreme conditions**

--Graceful degradation of service instead of wide-spread blackouts

--Resilient service during extreme events

Ilic, M., Korpås, M., & Jaddivada, R. (2020). Interactive Protocols for Distributed Energy Resource Management Systems (DERMS). *IET Generation, Transmission & Distribution*.
Ilic, M.D., Lang, J.H. and Allen, E.H., 2007, August. The role of numerical tools in maintaining reliability during economic transfers an illustration using the npcc equivalent system model. In *2007 iREP Symposium-Bulk Power System Dynamics and Control-VII. Revitalizing Operational Reliability* (pp. 1-13). IEEE.

Challenges—It may not work!

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

-- Highly distributed decision makers

--Minimal coordination of interactions

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

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

MIT cloud implementation and demo—
DyMonDS –based Scalable Electric Power System Simulator

- Platform design alternatives considered
- Control/communication framework -dependent physical and economic outcomes
- Rationale for selecting control/communication framework for MIT cloud SRR implementation
- Lessons learned on Pecan Street data –meeting ARPA-E performance metrics with a mix of DER resources

Preliminary Conclusions

- 97 water heaters would not be sufficient to meet ARPA-E targeted performance metrics
  - RMT – The number is not sufficient;
  - RMVT – Behavior patterns variability can’t be estimated;
  - The effect of bids is so week when there is no consumption;
  - During large sudden consumptions, DERs ratings typically exceeded and they opt out.
- Addition of EVs and batteries meets the criteria fully (live SEPSS demo)
- Approach 3 does not require huge number of devices (Physics-based modeling and control combined with cloud- supported incentives for efficient performance at value)
- Publications describe more detail