Dynamic Monitoring and Decision Systems (DyMonDS) Framework:

Toward Making the Most Out of Available Electric Energy Technologies at Value

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DIMACS Center, CoRE Building, Rutgers University

Outline

- Importance of the area; new problem; what needs fixing and why; questionable practices
- DyMonDS framework for integrating at value- proof-of-concept simulator
- Physical, information and economic incentives closely aligned
- The key challenge—integrate combinations of technologies at value (non-unique designs, OK as long as G,T and D work together to add value to the system as a whole)
- Examples of value of different technologies

Importance of electric energy services

- Critical national infrastructure
- Huge part of US economy (>$200 billion business)
- Major source of carbon footprint
- Potential large user of cyber technologies
- Industrialized economy depends on low-cost electricity service

It works today, but…

- Increased frequency and duration of service interruption (effects measured in billions)
- Major hidden inefficiencies in today's system (estimated 25% economic inefficiency by FERC)
- Deploying high penetration renewable resources is not sustainable if the system is operated and planned as in the past (``For each 1MW of renewable power one would need .9MW of flexible storage in systems with high wind penetration" –clearly not sustainable)
- Long-term resource mix must serve long-term demand needs well

New systems engineering challenge

- Not a best effort problem; guaranteed performance
- Highly nonlinear dynamics
- Complex time-space scales in network systems (milliseconds—10 years; one town to Eastern US)
- Inadequate storage
- Large-scale optimization under uncertainties
- Complex large-scale dynamic networks (energy and cyber)
- Information and energy processing intertwined
- Framework required for ensuring guaranteed performance (no single method will do it!)

Making the most out of the naturally available resources?
THE PROBLEM WE SHOULD SOLVE[1]

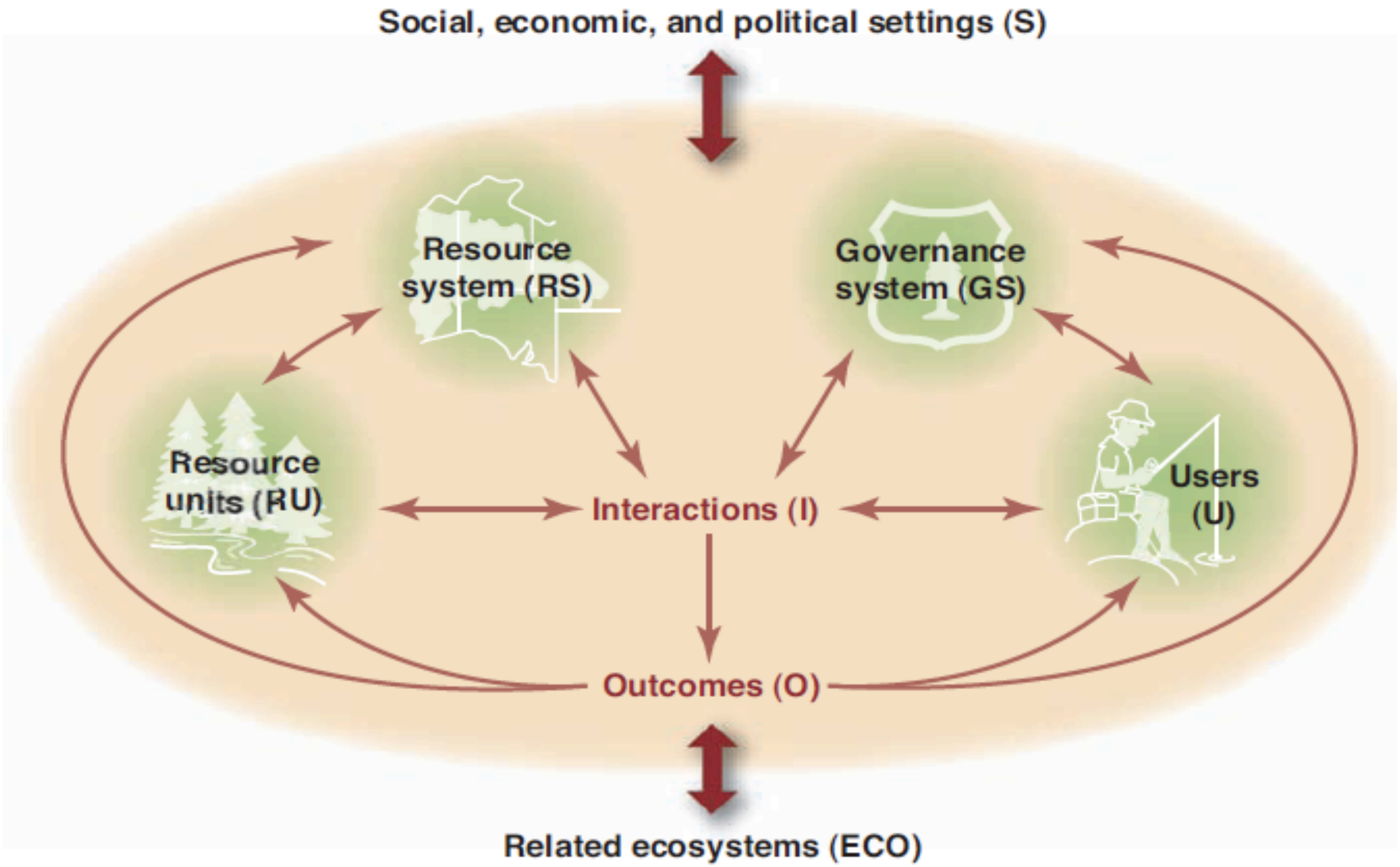
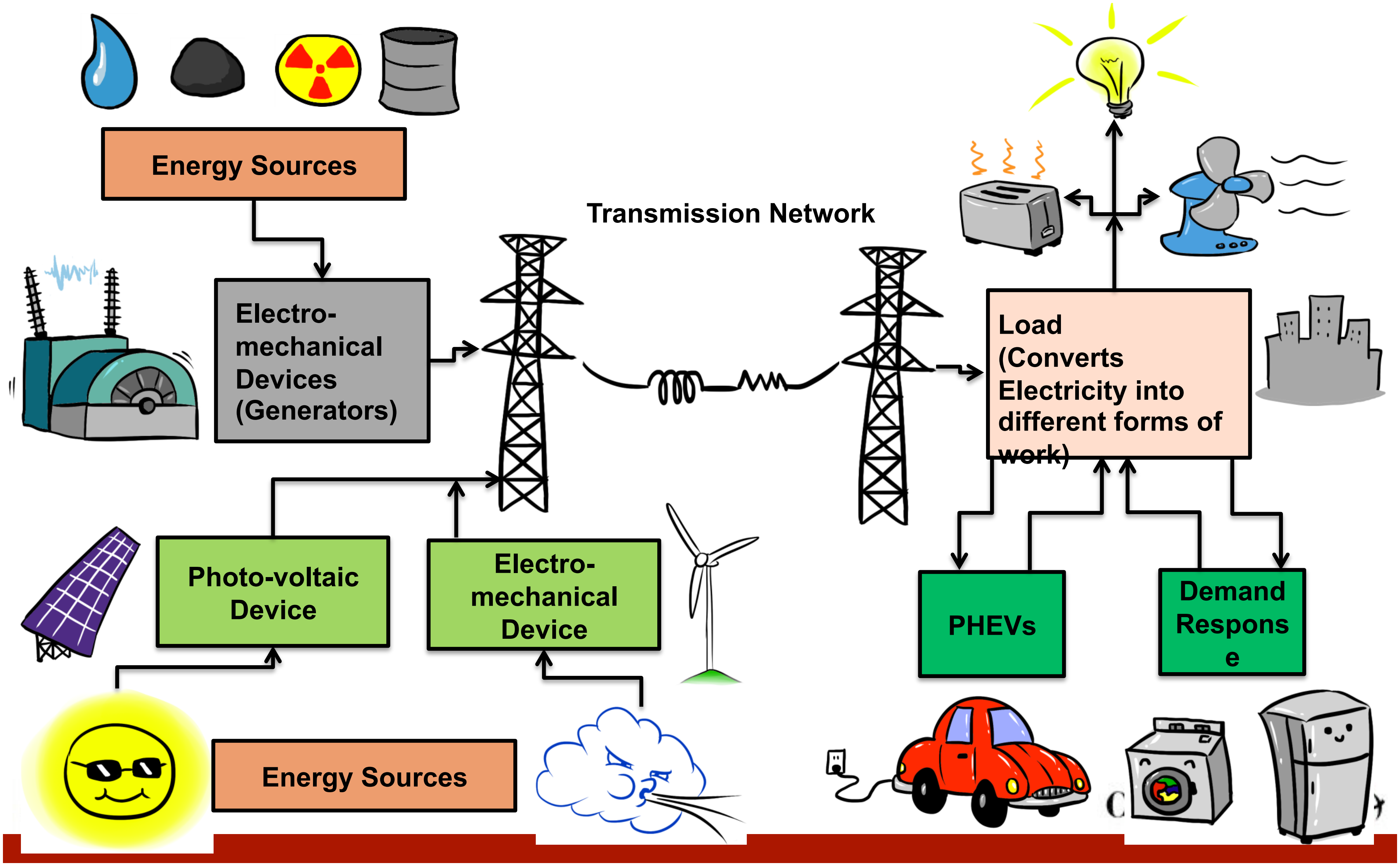


Fig. 1. The core subsystems in a framework for analyzing social-ecological systems.

Future Power Systems-Diverse Physics



Energy Sources

Electro-mechanical Devices (Generators)

Transmission Network

Load (Converts Electricity into different forms of work)

Photo-voltaic Device

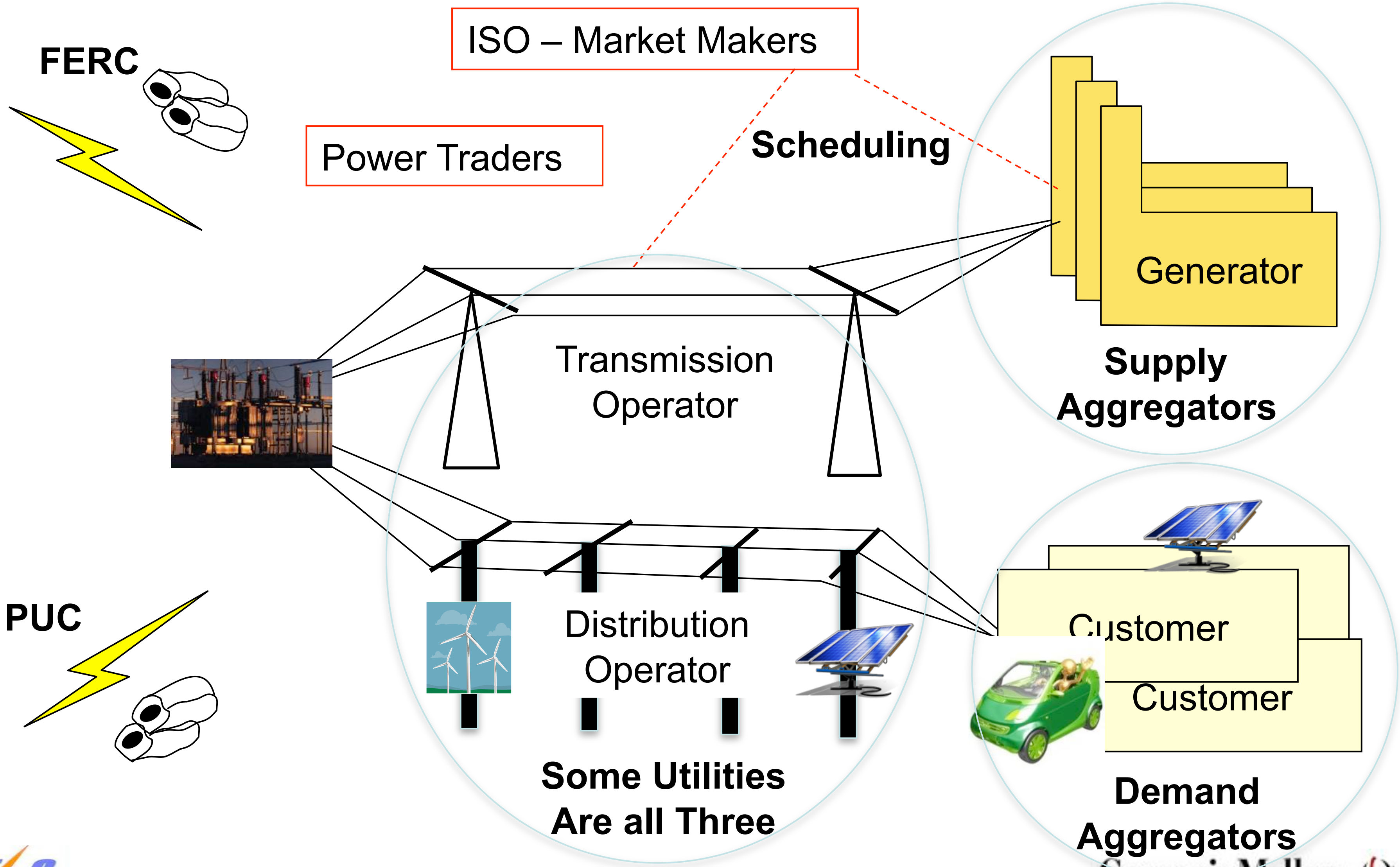
Electro-mechanical Device

PHEVs

Demand Response

Energy Sources

Contextual complexity



FERC

ISO – Market Makers

Power Traders

Scheduling

Generator

Supply Aggregators

Transmission Operator

PUC

Distribution Operator

Customer

Customer

Some Utilities Are all Three

Demand Aggregators

“Smart Grid” ←→ electric power grid and ICT for sustainable energy systems [2]

Core Energy Variables

- Resource system (RS)
- Generation (RUs)
- Electric Energy Users (Us)

Man-made Grid

- Physical network connecting energy generation and consumers
- Needed to implement interactions

Man-made ICT

- Sensors
- Communications
- Operations
- Decisions and control
- Protection
- Needed to align interactions

Questionable practice

- **Nonlinear dynamics related**

  -Use of models which do not capture instability

  -All controllers are constant gain and decentralized (local)

  -Relatively small number of controllers

  -Poor on-line observability

- **Time-space network complexity related**

  -faster processes stable (theoretical assumption)

  -conservative resource scheduling (industry)

  -- weak interconnection

  --fastest response localized

  --lack of coordinated economic scheduling

  -- linear network constraints when optimizing resource schedules

  --preventive (the ``worst case") approach to guaranteed performance in abnormal conditions

DyMonDS Approach

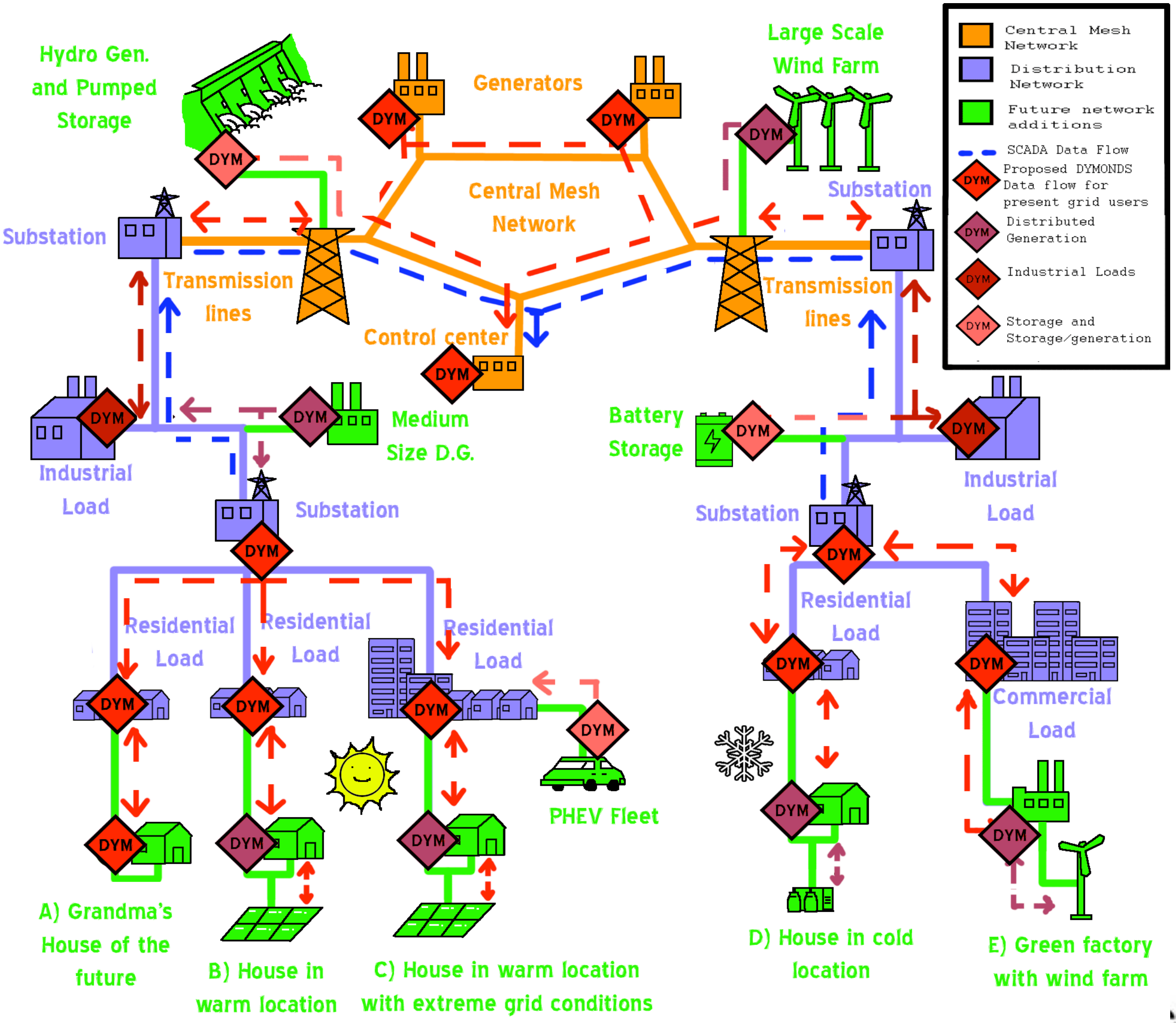
- Physics-based modeling and local nonlinear stabilizing control; new controllers (storage,demand control); new sensors (synchrophasors) to improve observability
- Divide and conquer over space and time when optimizing

  -DyMonDS for internalizing temporal uncertainties and risks at the resource and user level; interactive information exchange to support distributed optimization

  -perform static nonlinear optimization to account for nonlinear network constraints

  -enables corrective actions
- Simulation-based proof of concept for low-cost green electric energy systems in the Azores Islands [3]

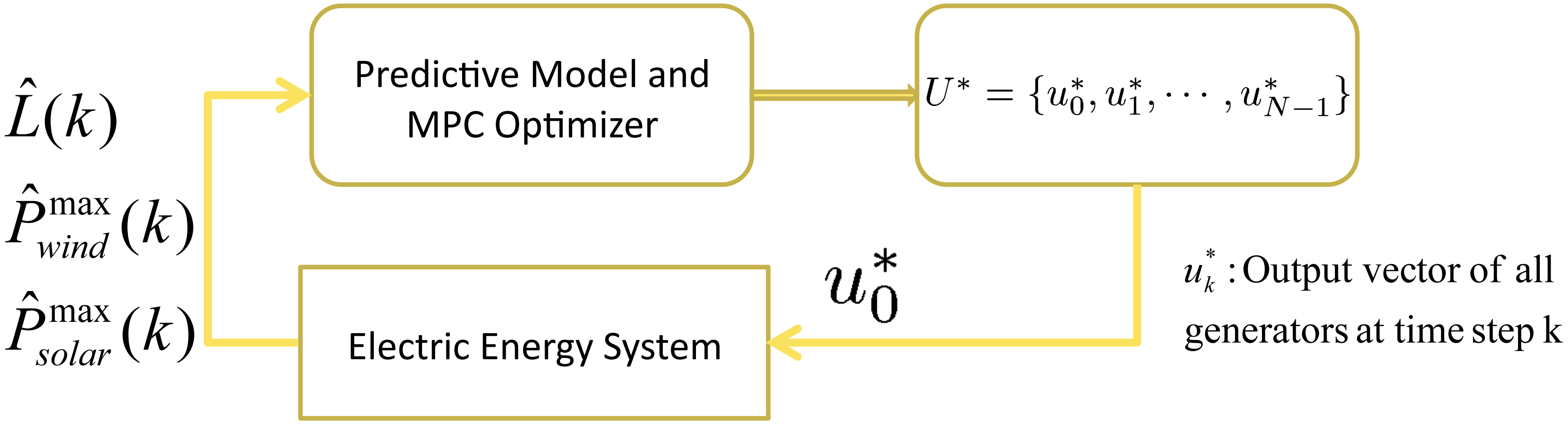
DYMONDS-enabled Physical Grid [2,3]



Minimally coordinated self-dispatch—DyMonDS [4,5]

- Distributed management of temporal interactions of resources and users
- Different technologies perform look-ahead predictions and optimize their expected profits given system signal (price or system net demand); they create bids and these get cleared by the (layers of) coordinators
- Putting Auctions to Work in Future Energy Systems
- DyMonDS-based simulator of near-optimal supply-demand balancing in an energy system with wind, solar, conventional generation, elastic demand, and PHEVs.

Centralized MPC –Benchmark



$\hat{L}(k)$

$\hat{P}_{wind}^{\max}(k)$

$\hat{P}_{solar}^{\max}(k)$

Predictive Model and MPC Optimizer

$U^* = \{u_0^*, u_1^*, \cdots, u_{N-1}^*\}$

u_0^*

Electric Energy System

u_k^* : Output vector of all generators at time step k

- Predictive models of load and intermittent resources are necessary.
- Optimization objective: minimize the total generation cost.
- Horizon: 24 hours, with each step of 5 minutes.

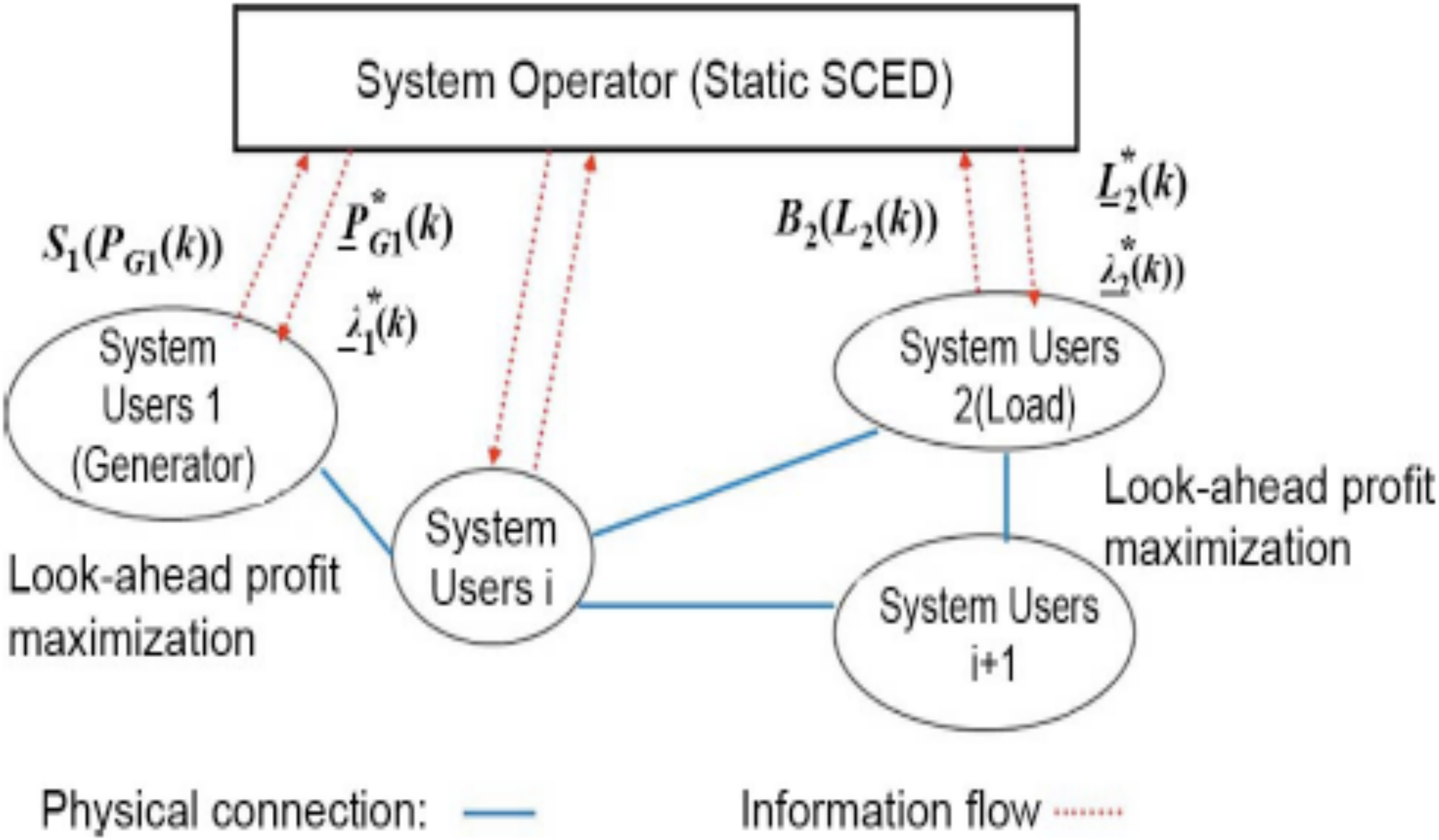
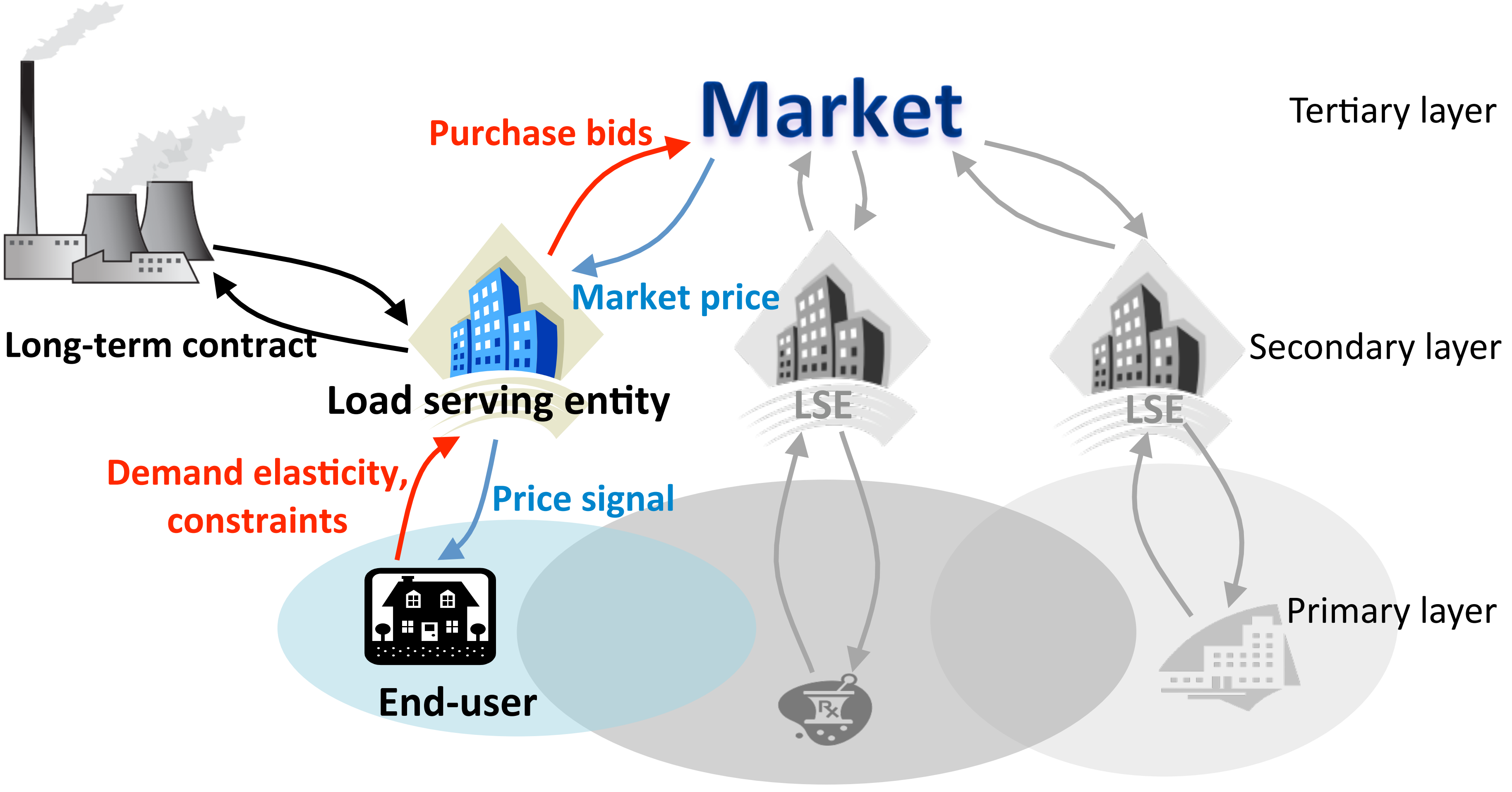


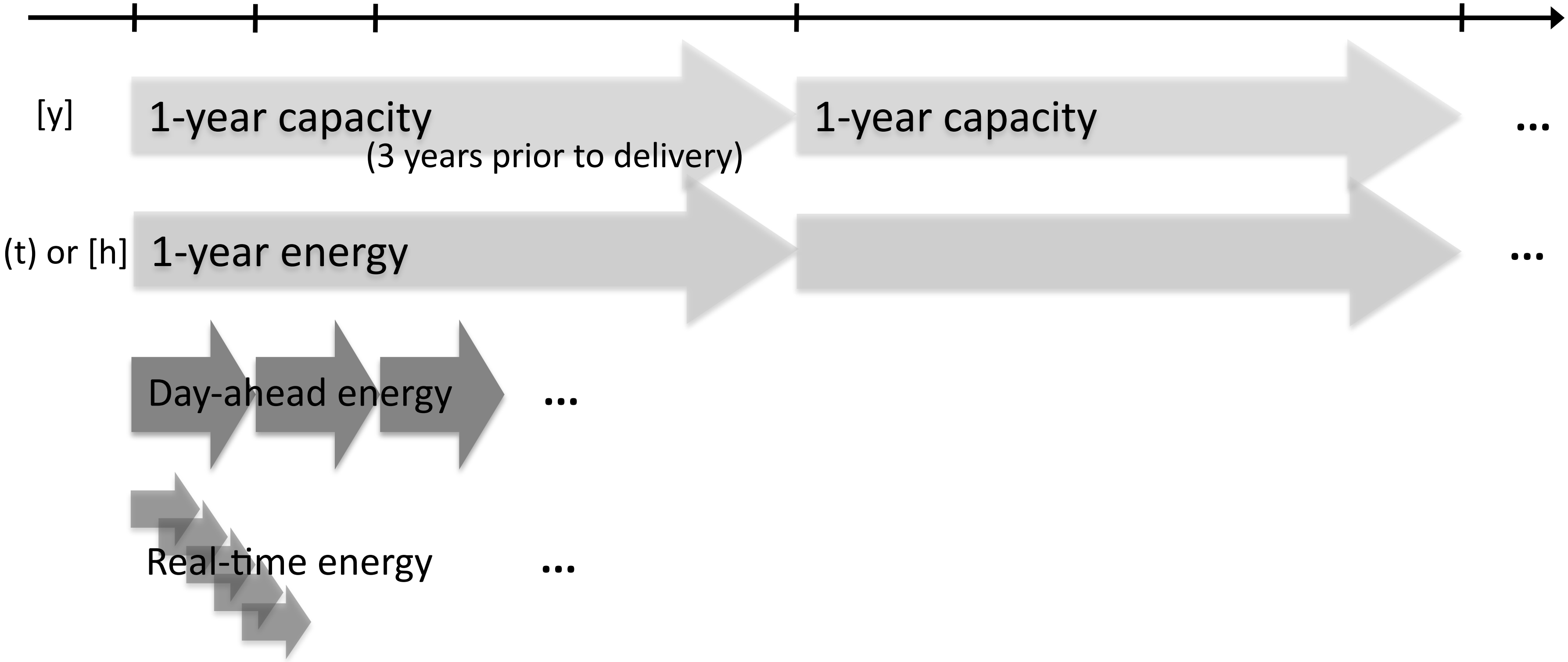
Fig. 3. Required information exchange for DYMONDS-based dispatch.

Proposed framework – adaptive load management (ALM) [6-9]



Power plant drawing by Catherine Collier, Integration and Application Network, University of Maryland Center for Environmental Science (ian.umces.edu/imagelibrary/)

Multi-temporal decision making timeline



[y] 1-year capacity (3 years prior to delivery) 1-year capacity …

(t) or [h] 1-year energy …

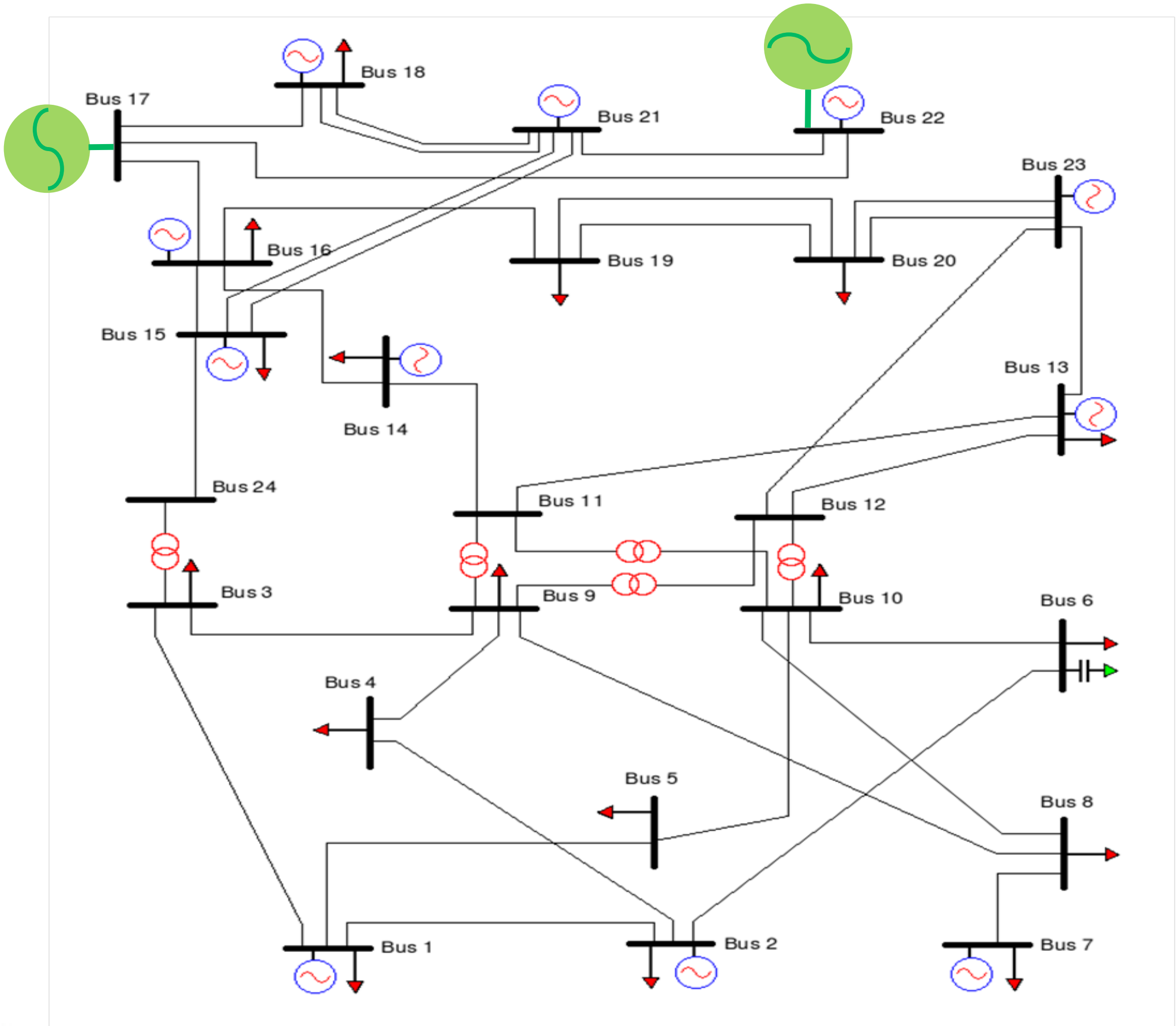
Day-ahead energy …

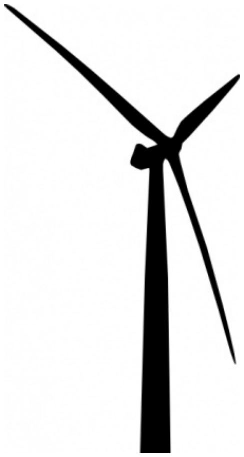
Real-time energy …

Objective of optimization [4,5]

$\min_{P_G,L} \sum_{k=1}^{K} (\sum_{i \in G} (C_i(P_{G_i}(k))) - \sum_{z \in Z} (B_z(L_z(k))))$	Total cost – benefit
$s.t. \sum_{i \in G} P_{G_i}(k) = \sum_{z \in Z} L_z(k);$	Demand = supply
$\hat{P}_{G_j}^{max}(k) = g_j(\hat{P}_{G_j}^{max}(k-1)), j \in G_r;$	Forecasted availability of renewable resources
$\hat{P}_{G_j}^{min}(k) = h_j(\hat{P}_{G_j}^{min}(k-1)), j \in G_r;$	
$\hat{P}_{G_j}^{\min}(k) \leq P_{G_j}(k) \leq \hat{P}_{G_j}^{\max}(k), j \in G_r;$	Renewable's capacity constraints
$0 \leq L_z(k) \leq L_z^{max}, z \in Z;$	Load's "capacity" constraints
$x_z(k+1) = g_z(L_z(k), x_z(k), \theta_z(k)), z \in Z;$	Load dynamics
$P_{G_i}^{\min}(k) \leq P_{G_i}(k) \leq P_{G_i}^{\max}(k), i \in G \setminus G_r;$	Traditional resources capacity
$\lvert P_{G_i}(k+1) - P_{G_i}(k) \rvert \leq R_i, i \in G;\ \text{and},$	Traditional resources' ramp rates
$\lvert F(k,P,L) \rvert \leq F^{max} \quad \forall k$	Transmission constraints

DYMONDS Simulator
IEEE RTS with Wind Power [10]

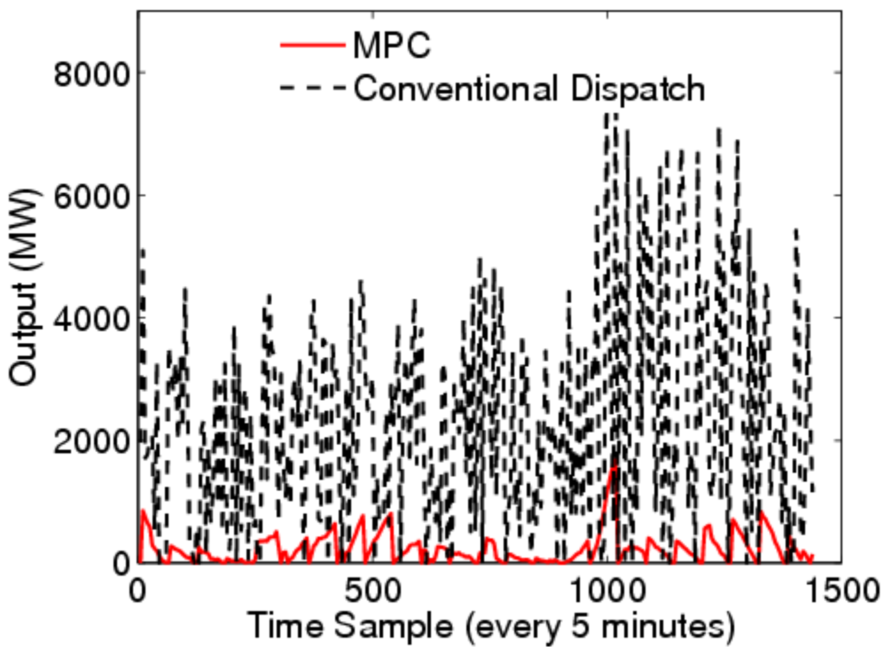




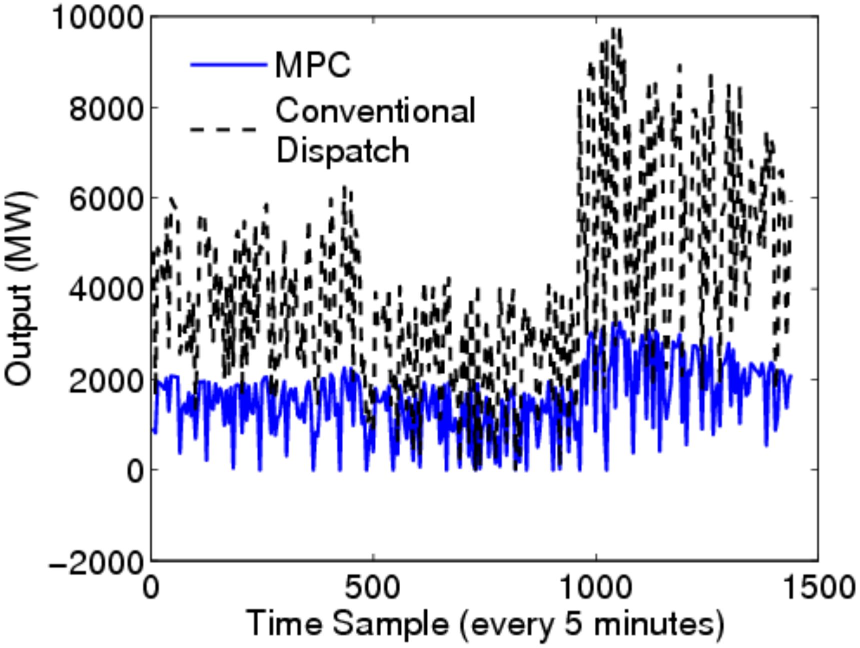
- 20% / 50% penetration to the system [4,5]

Conventional cost over 1 year *	Proposed cost over the year	Difference	Relative Saving
$ 129.74 Million	$ 119.62 Million	$ 10.12 Million	7.8%

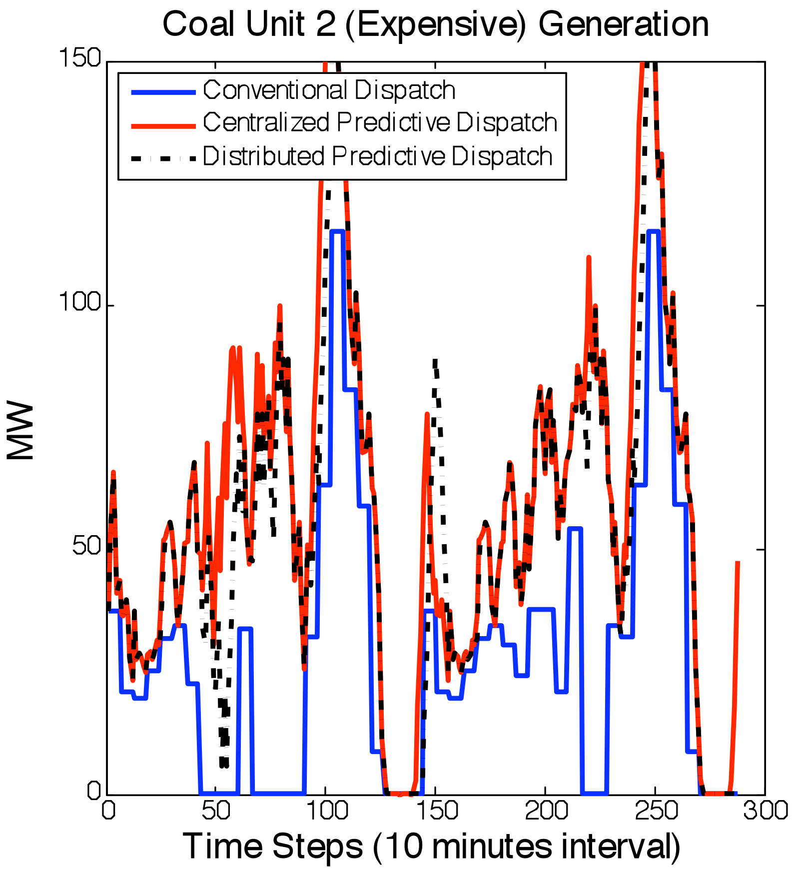
Natural Gas Power Plant Output under Two Cases

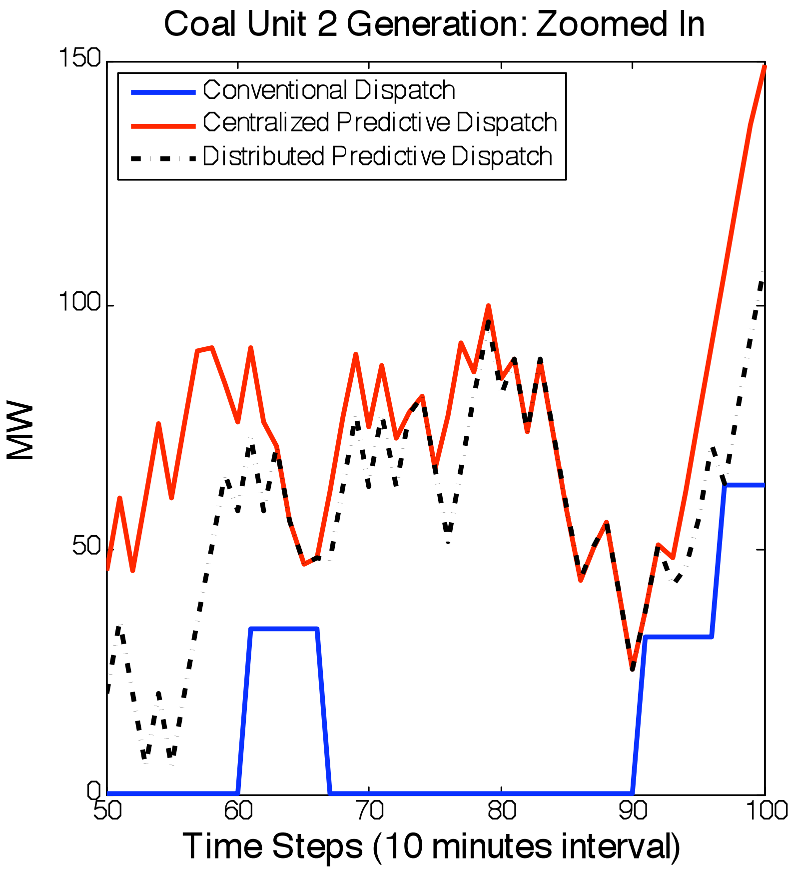


Wind Power Output under Two Cases



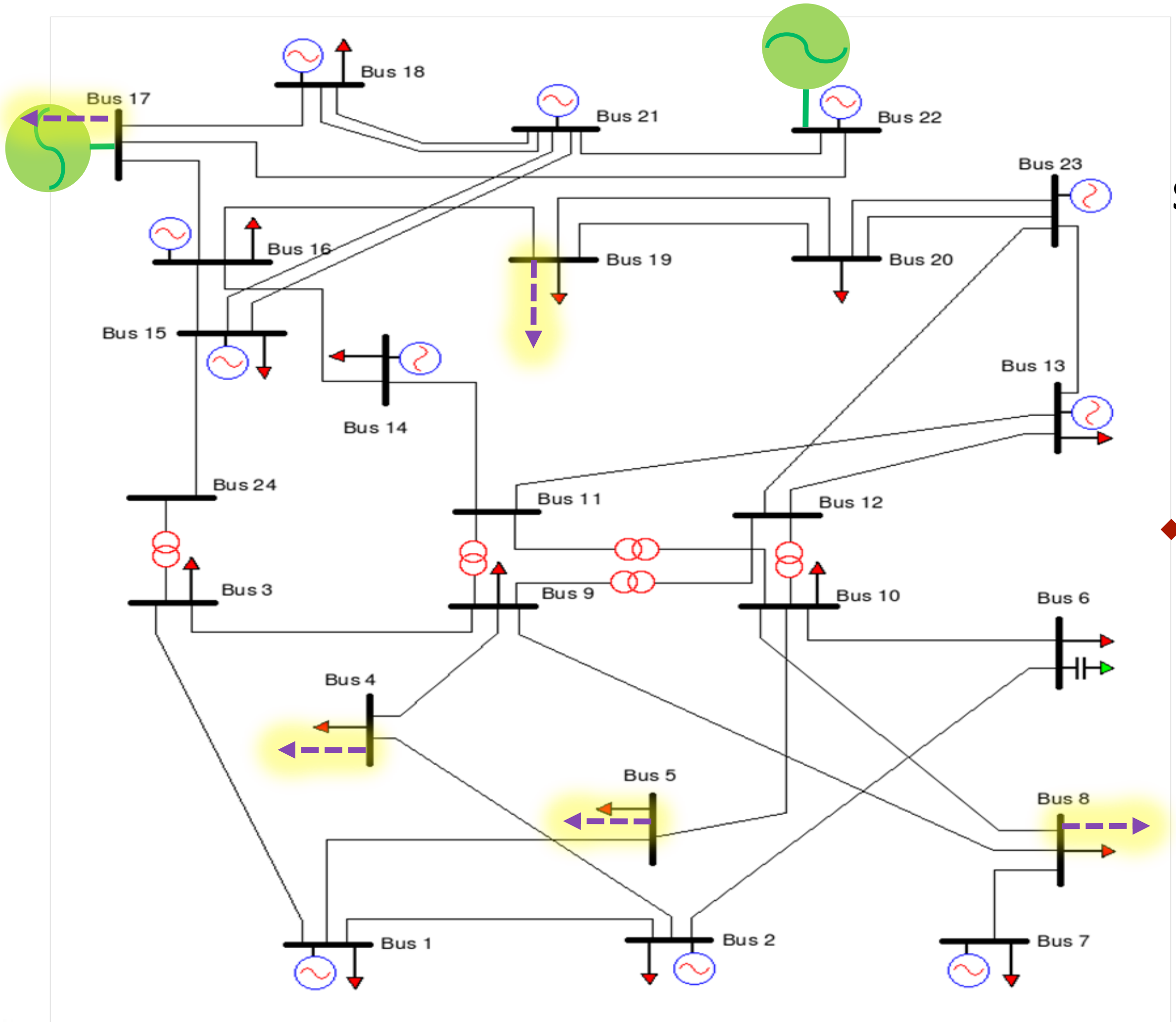
*: load data from New York Independent System Operator, available online at http://www.nyiso.com/public/market_data/load_data.jsp

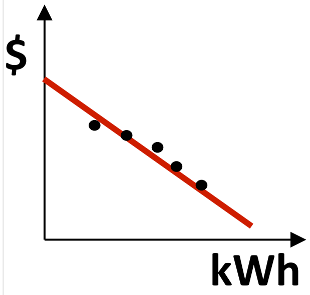




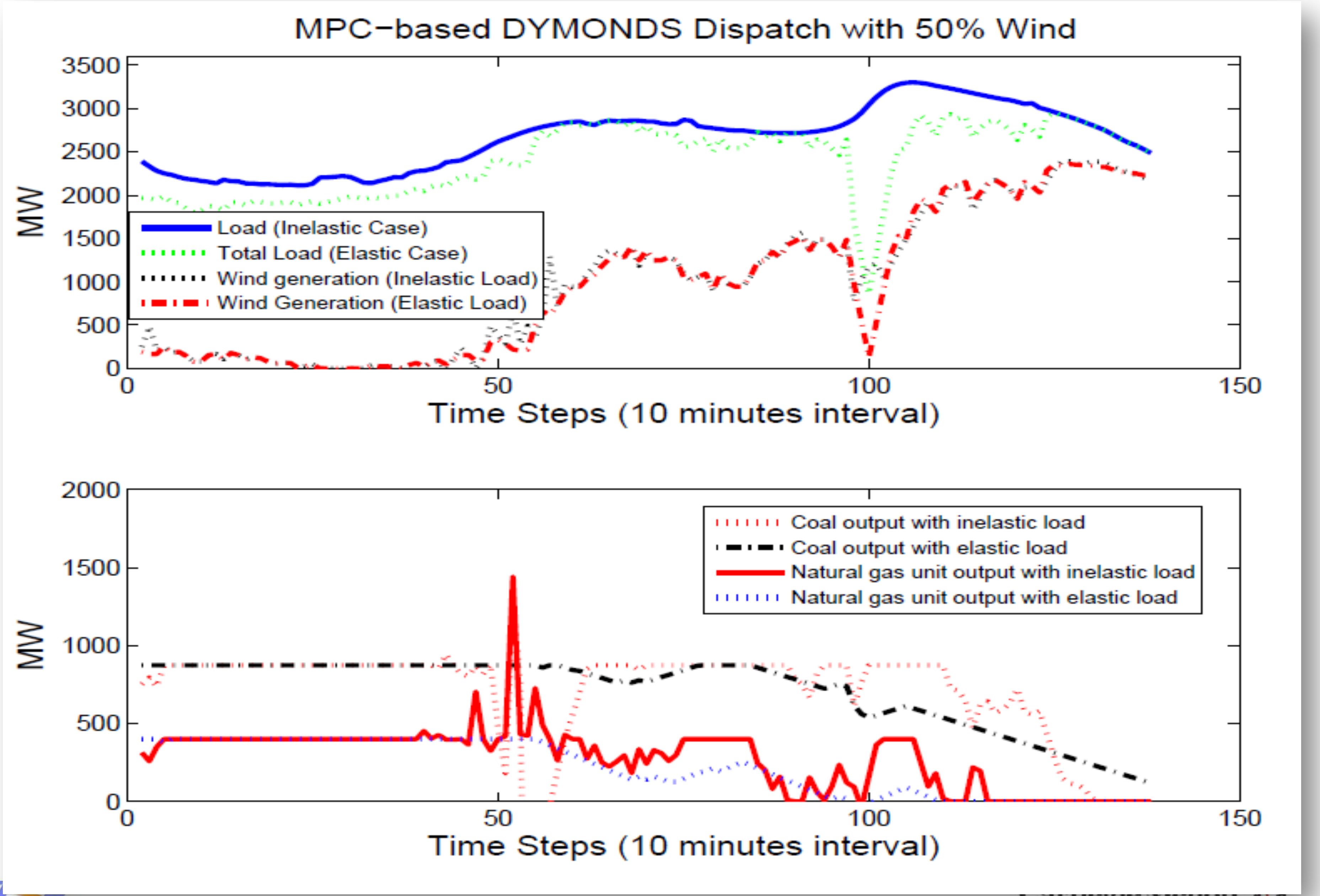
BOTH EFFICIENCY AND RELIABILITY MET

DYMONDS Simulator
Impact of price-responsive demand

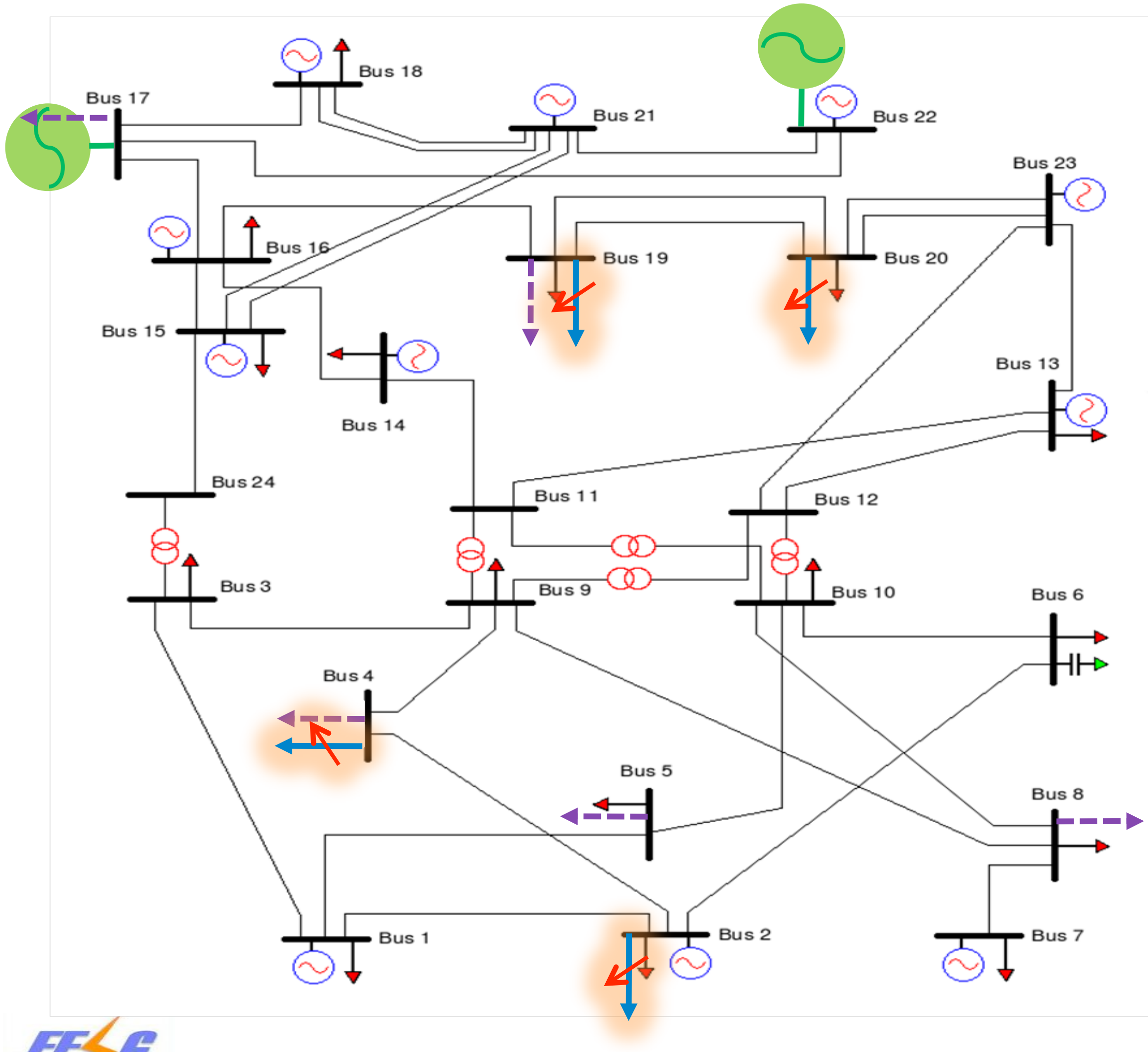




- Elastic demand that responds to time-varying prices

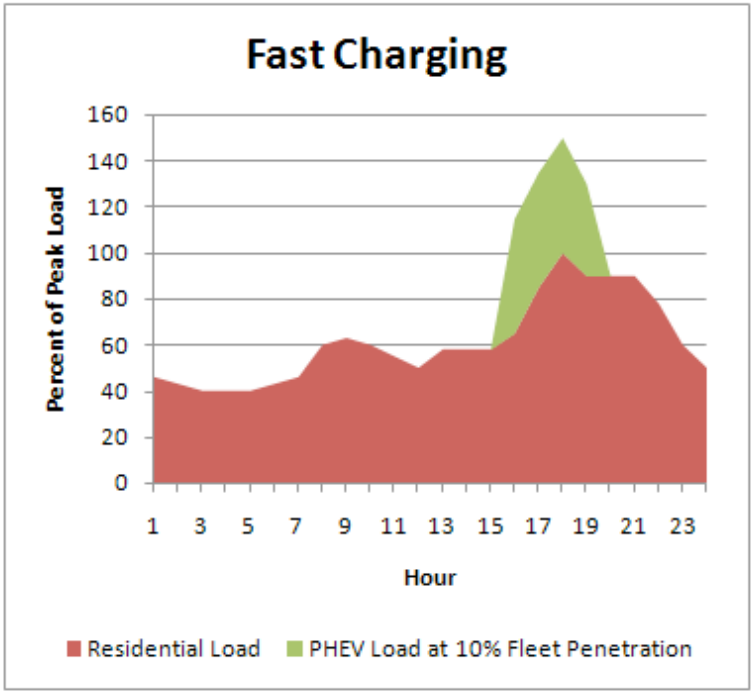

MPC−based DYMONDS Dispatch with 50% Wind
MW
3500
3000
2500
2000
1500
1000
500
0
0
50
100
150
Time Steps (10 minutes interval)
Load (Inelastic Case)
Total Load (Elastic Case)
Wind generation (Inelastic Load)
Wind Generation (Elastic Load)
MW
2000
1500
1000
500
0
0
50
100
150
Time Steps (10 minutes interval)
Coal output with inelastic load
Coal output with elastic load
Natural gas unit output with inelastic load
Natural gas unit output with elastic load

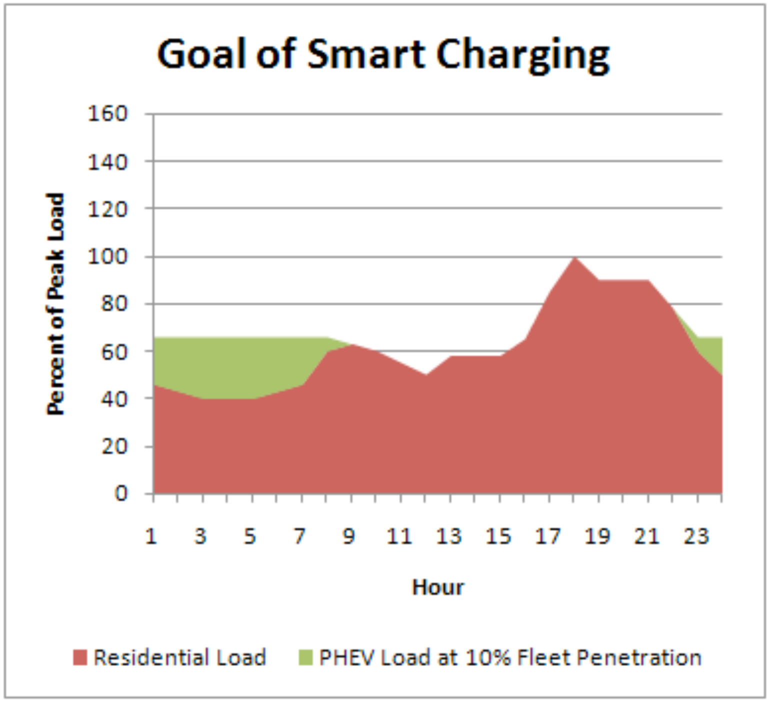
DYMONDS Simulator
Impact of Electric vehicles [10-12]

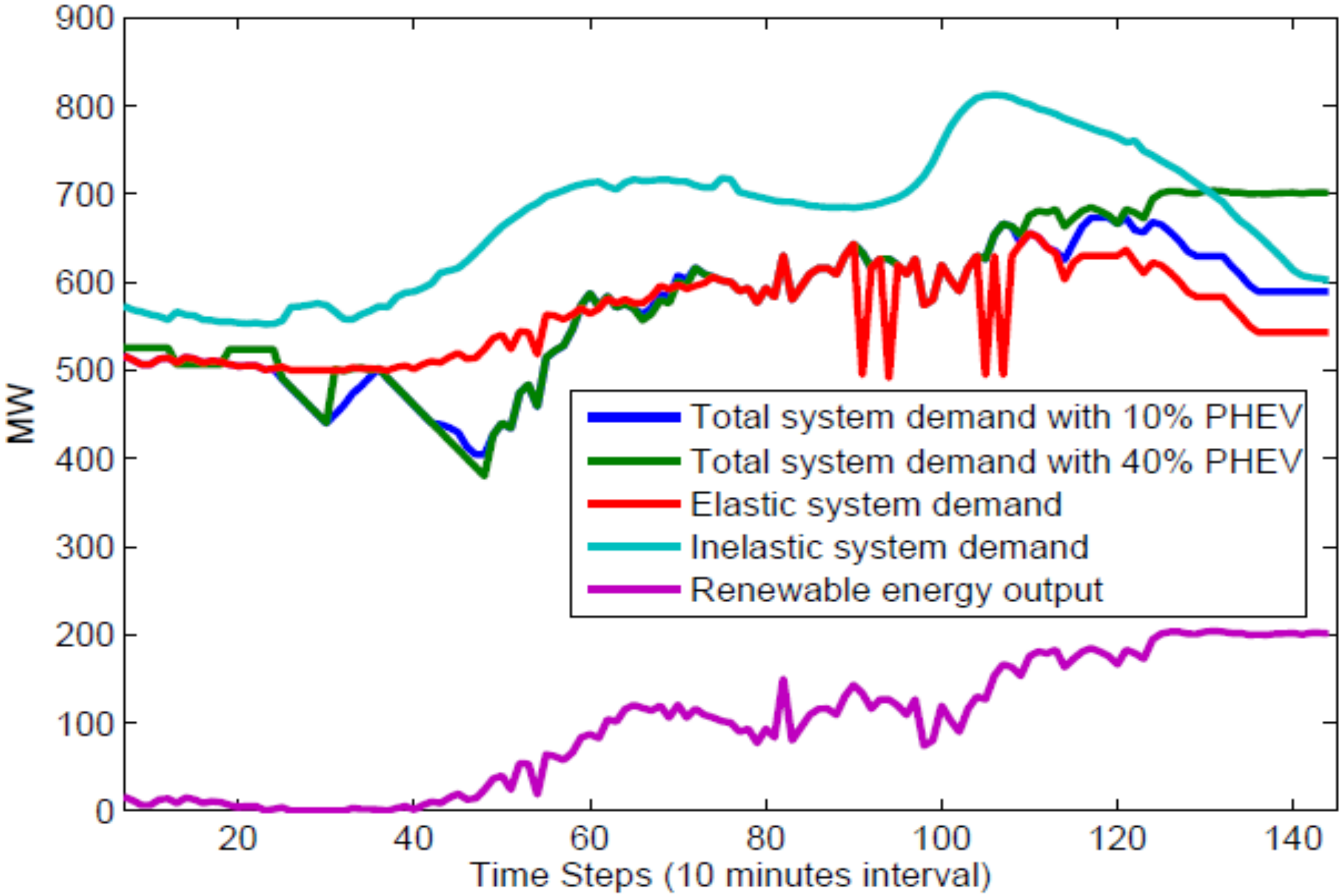


- ❖ Interchange supply / demand mode by time-varying prices

Optimal Control of Plug-in-Electric Vehicles: Fast vs. Smart


Fast Charging


Goal of Smart Charging


MW
0
100
200
300
400
500
600
700
800
900
20
40
60
80
100
120
140
Time Steps (10 minutes interval)
Total system demand with 10% PHEV
Total system demand with 40% PHEV
Elastic system demand
Inelastic system demand
Renewable energy output

Large-Scale Nonlinear Network Optimization for Corrective Actions [13,14]

Imports can be increased by the following:

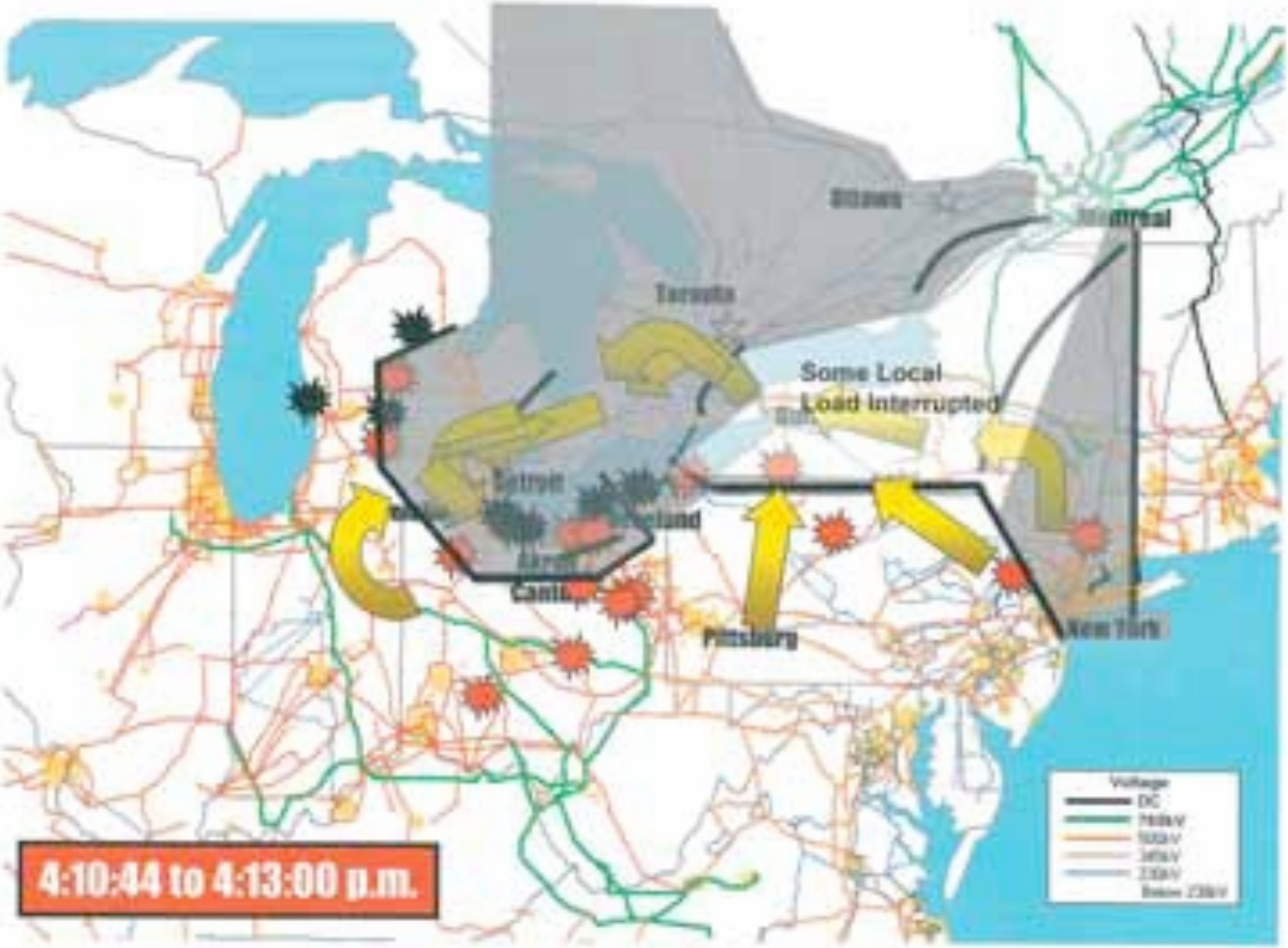
- More reliable dynamic rating of line limits
- Optimal generator voltages
- Optimal settings of grid equipment (CBs, OLTCs, PARs, DC lines, SVCs)
- Demand-side management (identifying load pockets with problems)
- Optimal selection of new equipment (type, size, location)

Natural reduction of losses, reduction of VAR consumption, reduction of equipment stress

LSS Nonlinear Network Optimization for Corrective Actions

Imports can be increased by scheduling:

- ❖Optimal generator voltages
- ❖Optimal settings of grid equipment (CBs, OLTCs, PARs, DC lines, SVCs)
- ❖Demand-side management (identifying load pockets with problems)
- ❖Natural reduction of losses, reduction of VAR consumption, reduction of equipment stress
- ❖Studies have shown 20-25% economic efficiency by implementing corrective actions

Ottawa
Montreal
Toronto
Some Local
Load Interrupted
Detroit
eland
Akron
Canton
Pittsburg
New York
Voltage
DC
765kV
500kV
345kV
230kV
Below 230kV
4:10:44 to 4:13:00 p.m.

The Key Role of Nonlinear LSS Network Optimization for Preventing Blackouts [13]

- Base case for the given NPCC system in 2002 and the 2007 projected load
- The wheel from PJM (Waldwick) through NYISO to IESO (Milton) –the maximum wheel feasible 100MW
- Optimized real power generation to support an increased wheel from PJM (Alburtis) through NYISO to IESO (Milton) –the maximum feasible wheel 1,200MW
- With the voltage scheduling optimized within +/- .03pu range, w/o any real power rescheduling the maximum power transfer increased to 2,900MW into both Alburtis and Waldwick;
- With the voltage scheduling optimized within +/- .05pu the feasible transfer increased to 3,100MW at both Alburtis and Waldwick
- With both voltages optimized within +/-.05pu and real power re-scheduled by the NYISO, the maximum wheel possible around 8,800MW

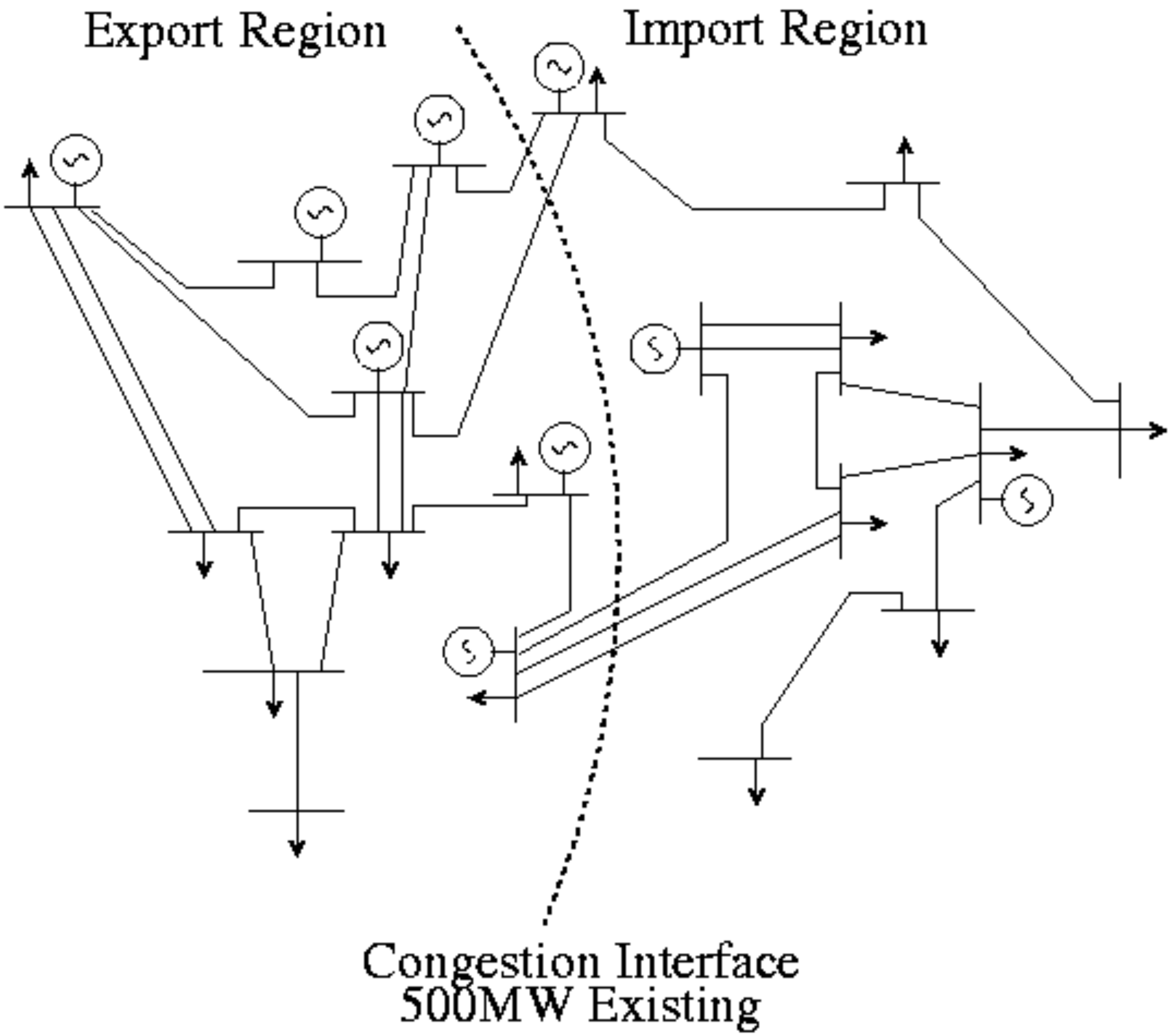
The key challenge: Framework for integrating combination of technologies at value [15]

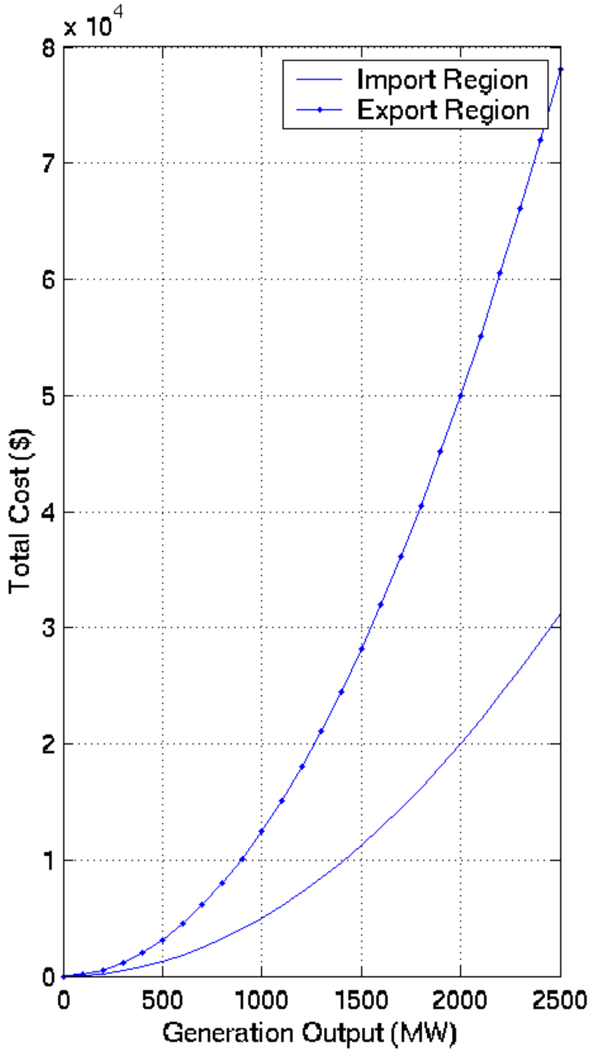
- Value is a system-dependent concept (time over which decision is made; spatial; contextual)
- Cannot apply capacity-based thinking; cannot apply short-run marginal cost thinking
- Reconciling economies of scope and economies of scale
- Value of flexibility (JIT,JIP, JIC) [2]
- Hardware, information, decision-making software; distributed, coordinated –all have their place and value

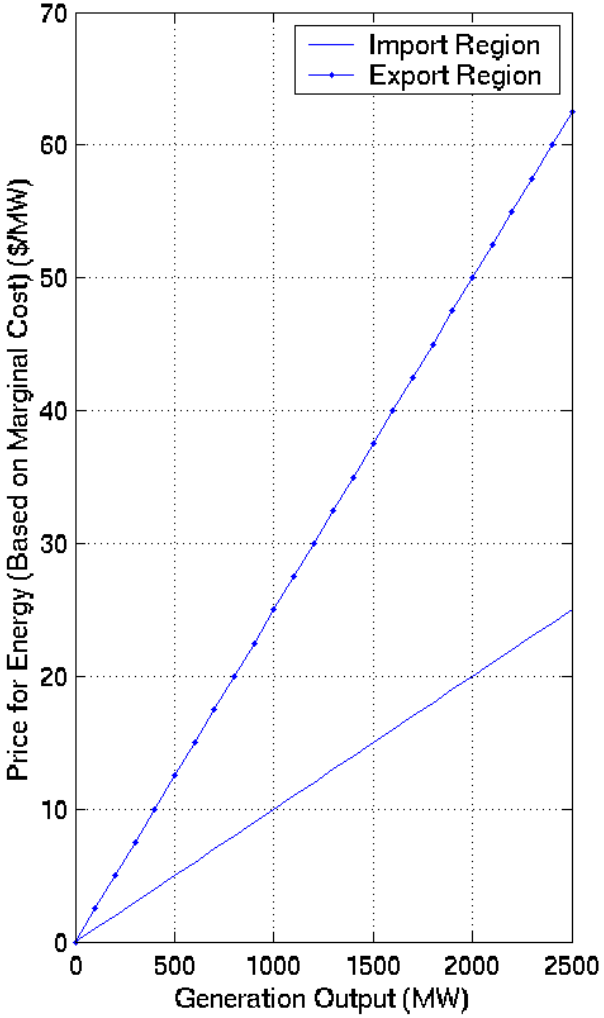
Examples of different values offered by different technologies

- ``Optimal grid” for thermal congestion relief [16]
- Passive wires vs. FACTS for managing wind power [17,18]
- State estimation to AC OPF; to SW [19]
- Learning, predictions, MIP for managing uncertainties
- ``De-constraining” technologies (nonlinear control for preventing voltage collapse [20,21]; FACTS [22,23] vs flywheel [24,25] for transient stabilization); nonlinear control of energy conversion [26]
- Reconfiguration of NOSs, NCSs for enabling use of DERs for differentiated reliability [27,28]
- PARs for making contract paths physical [29,30]

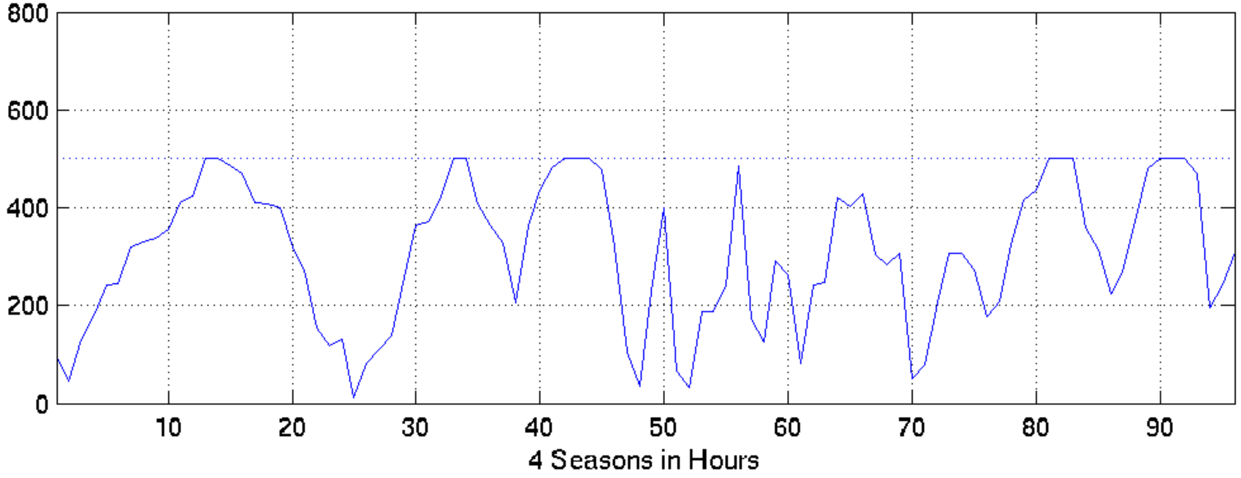
Optimal Grid for Congestion Relief—Value vs Cost [16]



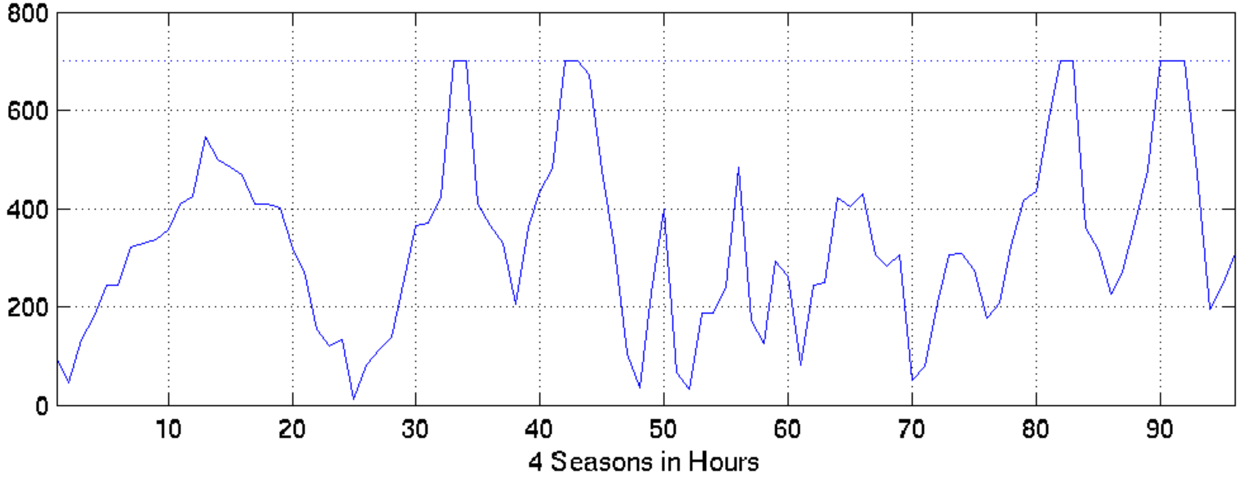

x 10^4
8
7
6
5
4
3
2
1
0
Total Cost ($)
0
500
1000
1500
2000
2500
Generation Output (MW)
Import Region
Export Region

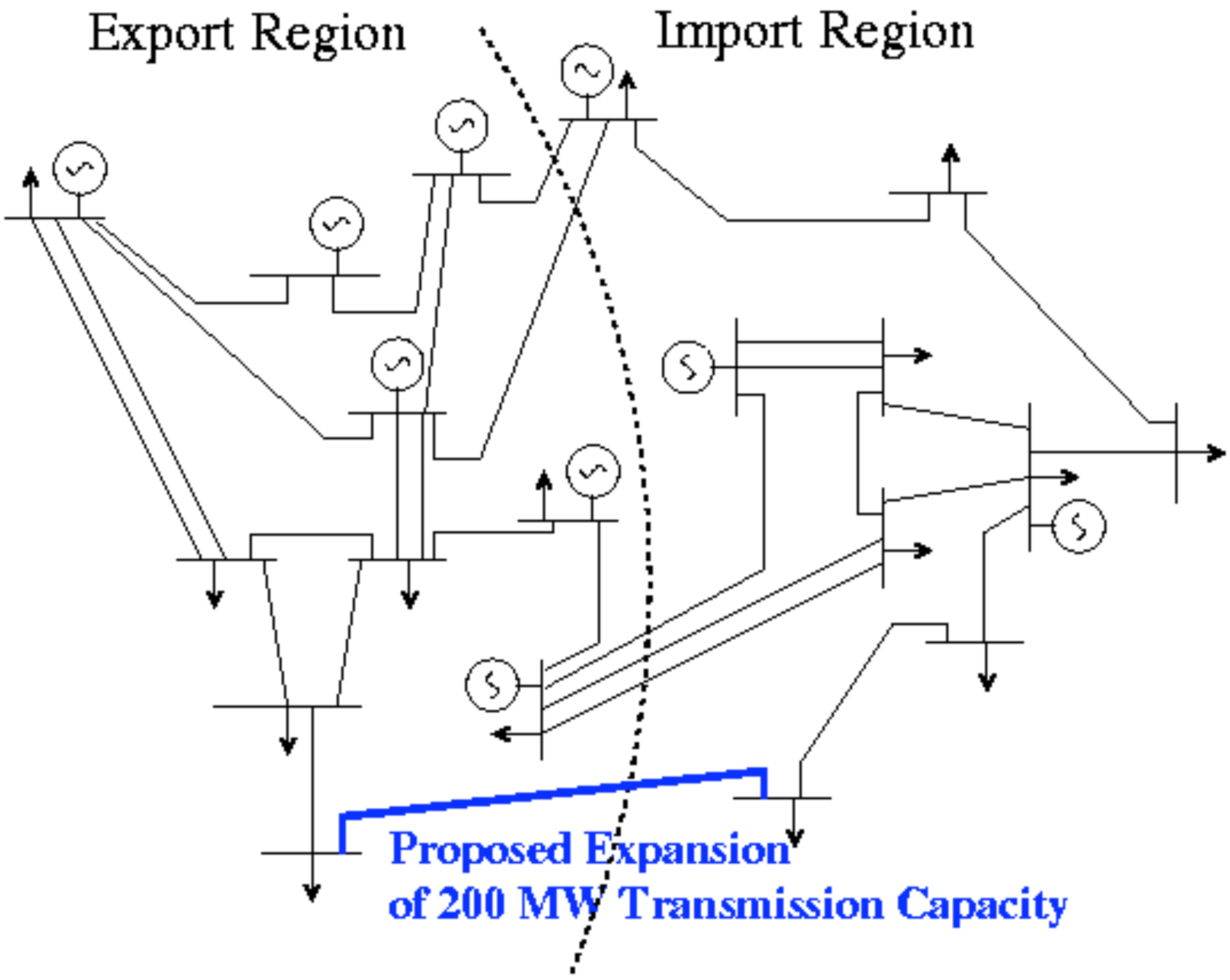

70
60
50
40
30
20
10
0
Price for Energy (Based on Marginal Cost) ($/MW)
0
500
1000
1500
2000
2500
Generation Output (MW)
Import Region
Export Region

Flow across the Congestion Interface (500MW)

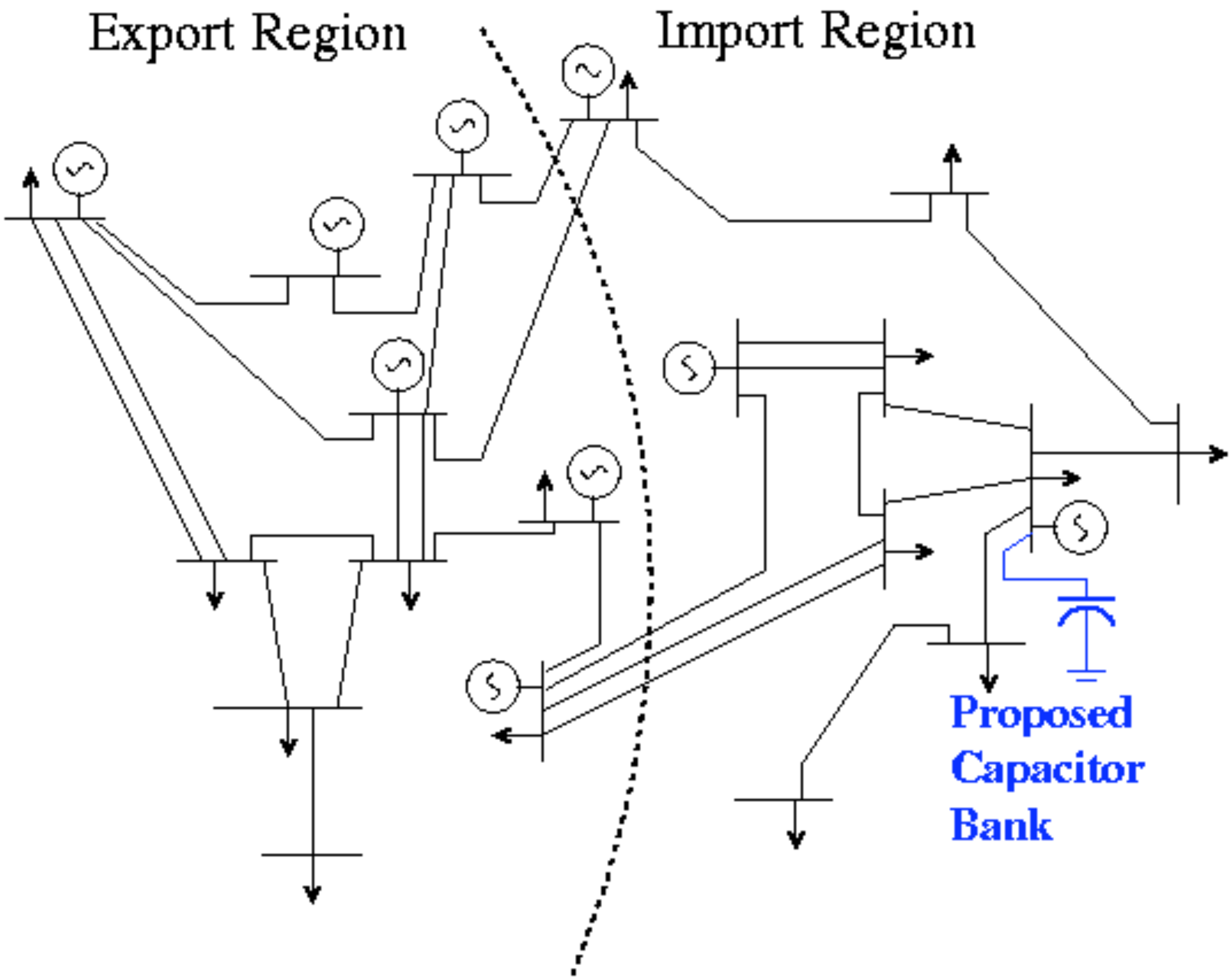


Flow across the Congestion Interface (700MW)

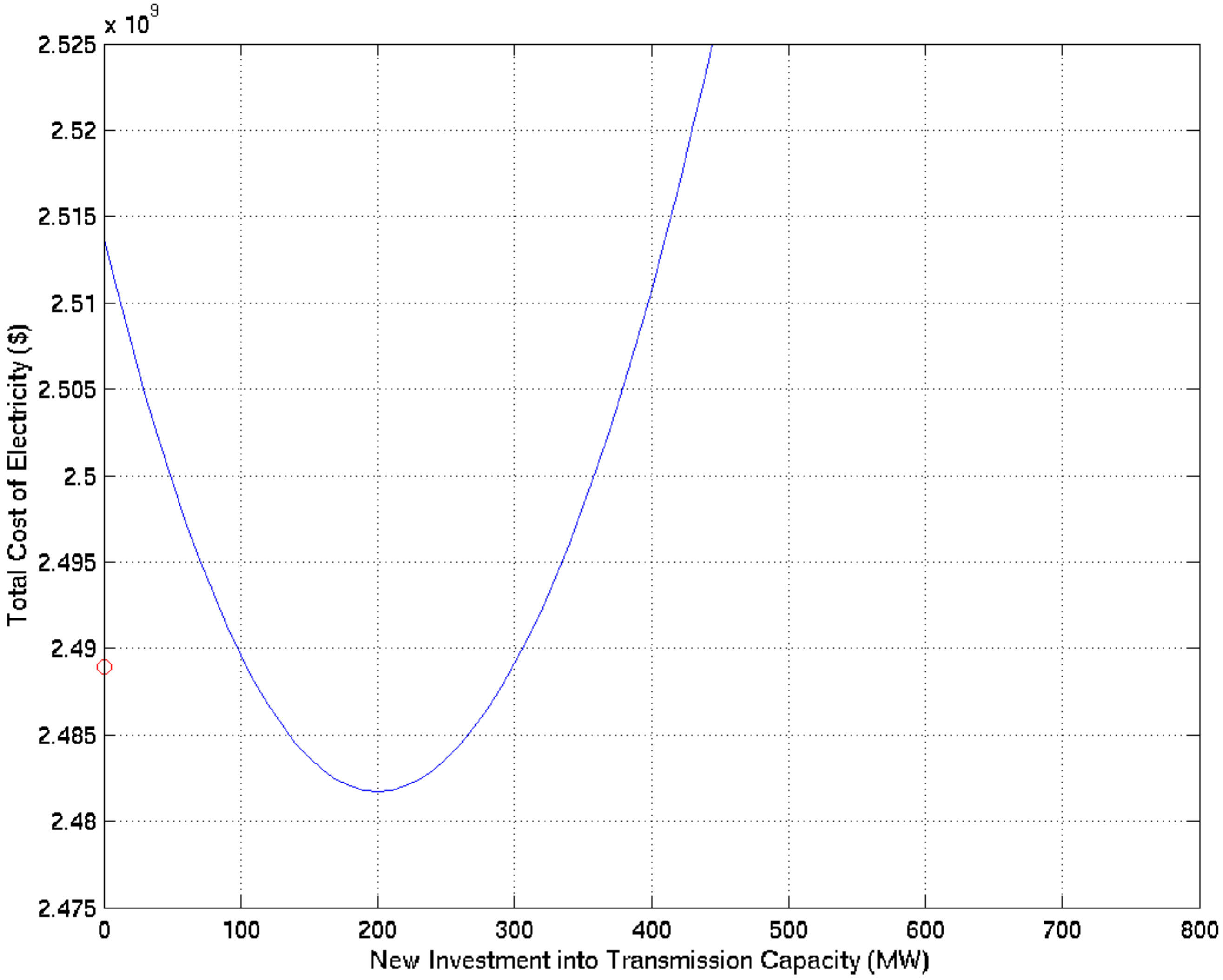


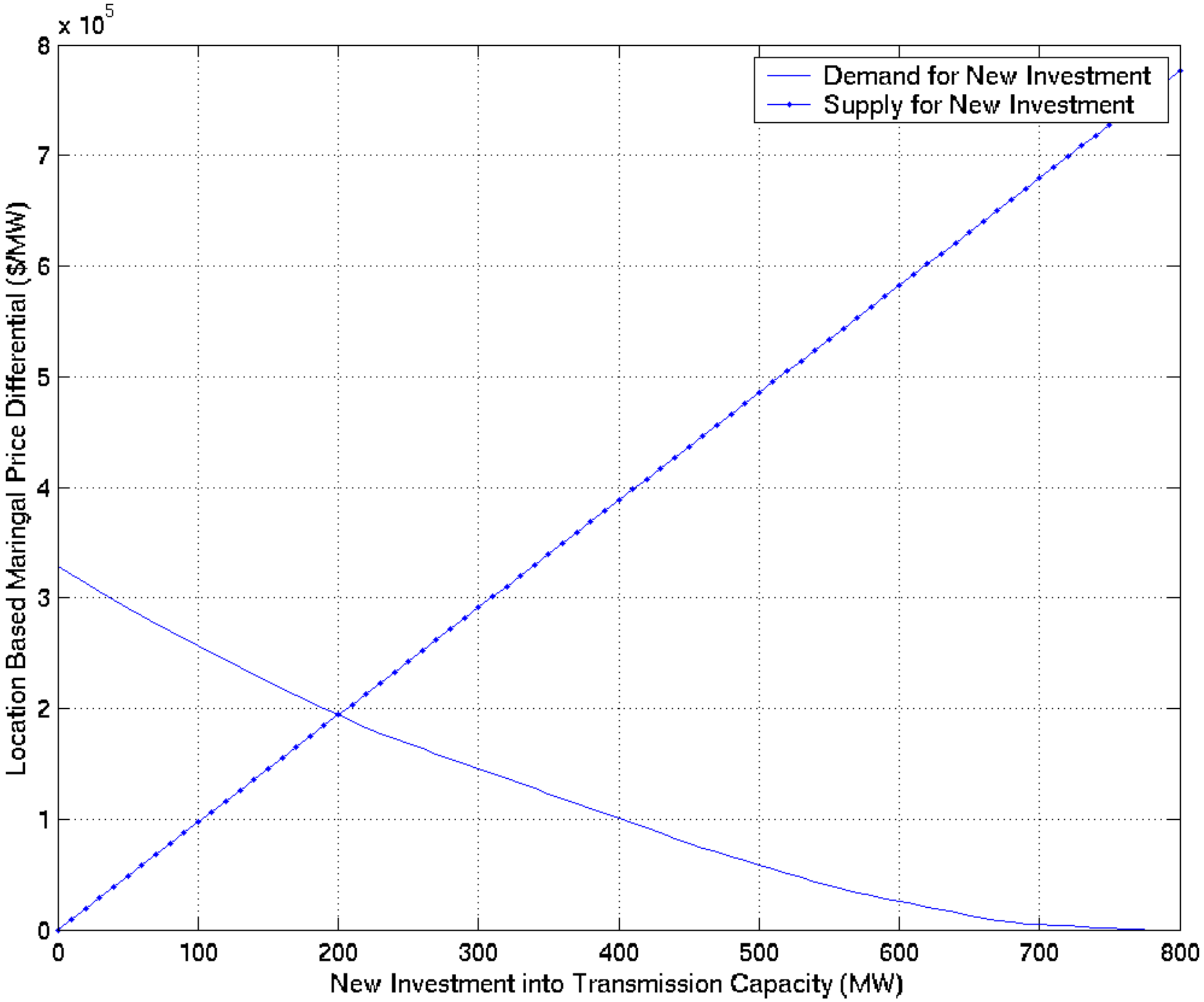


Proposed Expansion
of 200 MW Transmission Capacity


Export Region
Import Region
Proposed Capacitor Bank

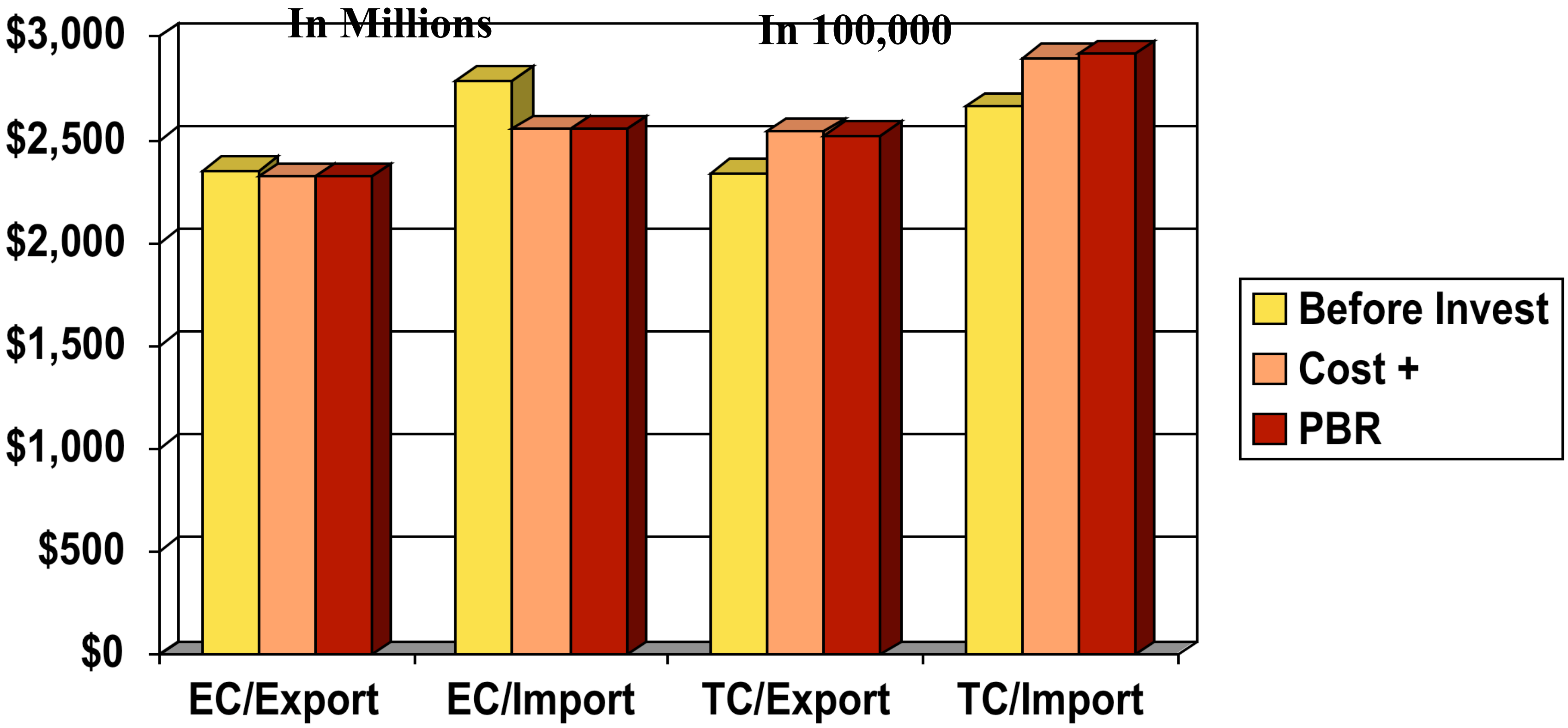
OPTIMAL GRID INVESTMENT!





x 10^5
8
7
6
5
4
3
2
1
0
0
100
200
300
400
500
600
700
800
Location Based Maringal Price Differential ($/MW)
New Investment into Transmission Capacity (MW)
Demand for New Investment
Supply for New Investment

Summary of Charges



Optimal Grid Investment Model [17,18]

$$\min_{K_l^y, x_f^y, P_n^{t,y}, x_{f,opt}^{t,y}} \sum_{y=1}^{Y} e^{-ry}[\sum_{t=1}^{T} \sum_{n=1}^{Ngen} c_{g,n(}P_n^{t,y}) + \sum_{l=1}^{Nline} (c_{k,l}(K_l^y) + c_{f,l}(x_{f,l}^y))]$$

Minimize Investment and Operational Cost

Subject to:

Operational Constraints

$$-\mathbf{K_{base}} - \sum_{\mathbf{i=1}}^{\mathbf{y}} \mathbf{K^i} \le \mathbf{F_{line}^{t,y}} = \mathbf{HP^{t,y}} \le \mathbf{K_{base}} + \sum_{\mathbf{i=1}}^{\mathbf{y}} \mathbf{K^i}$$

$$\sum_{b=1}^{Nbus} P_{d,b}^{t,y} - \sum_{n=1}^{Ngen} P_n^{t,y} = 0 \ \ for \ \forall \ \ t, y$$

$$P_n^{min} \le P_n^{t,y} \le P_n^{max} \ \ for \ \forall \ \ n, t, y$$

$$0 \le x_{f,opt,l}^{t,y} \le \sum_{i=1}^{y} x_{f,l}^i \ \ for \ \forall \ \ l, t, y$$

Investment Constraints

$$\sum_{i=1}^{y} x_{f,l}^i \le 0.5 x_{base,l} \ \ for \ \forall \ \ l, y$$

$$x_{f,l}^y \ge 0 \ \ for \ \forall \ \ l, y$$

$$K_l^y \ge 0 \ \ for \ \forall \ \ l, y$$

Optimality conditions for new line

$$\frac{\partial c_{k,l}}{\partial K_l^y} = \{\sum_{i=y}^{Y}\sum_{t=1}^{T}(\mu_l^{\top,t,i} + \mu_l^{\perp,t,i}) + \sum_{k=1}^{Nline}(\mu_l^{\perp,t,i} - \mu_l^{\top,t,i})\frac{\partial F_{line,k}^{t,i}}{\partial x_{new,l}^{y}}\}$$

Long-Run Marginal Cost of Investment in New Line **=** Marginal Value of Capacity of Line **+** Marginal Value of Reactance of Line

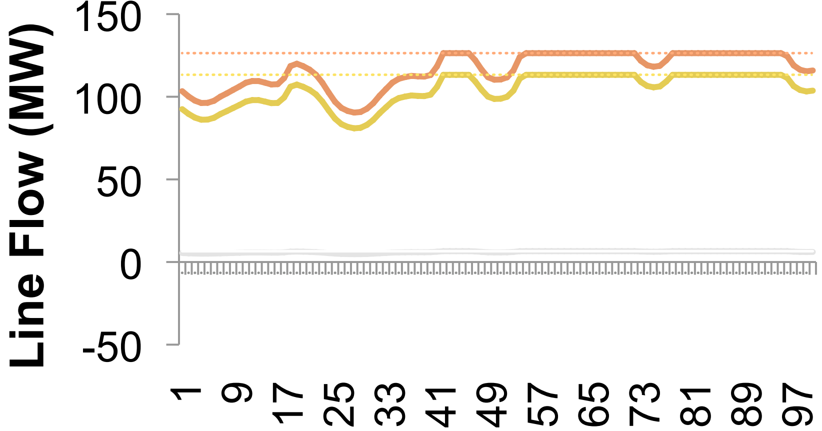
Optimality conditions for FACTS

$$\frac{\partial c_{f,l}}{\partial x_{f,l}^{y}} = \sum_{i=y}^{Y}\sum_{t=1}^{T}\sum_{k=1}^{Nline}(\mu_l^{\perp,t,i} - \mu_l^{\top,t,i})\frac{\partial F_{line,k}^{t,i}}{\partial x_{f,l}^{t,y}}$$

Long-Run Marginal Cost of Investment in FACTS **=** Marginal Value of Variable Reactance of Line

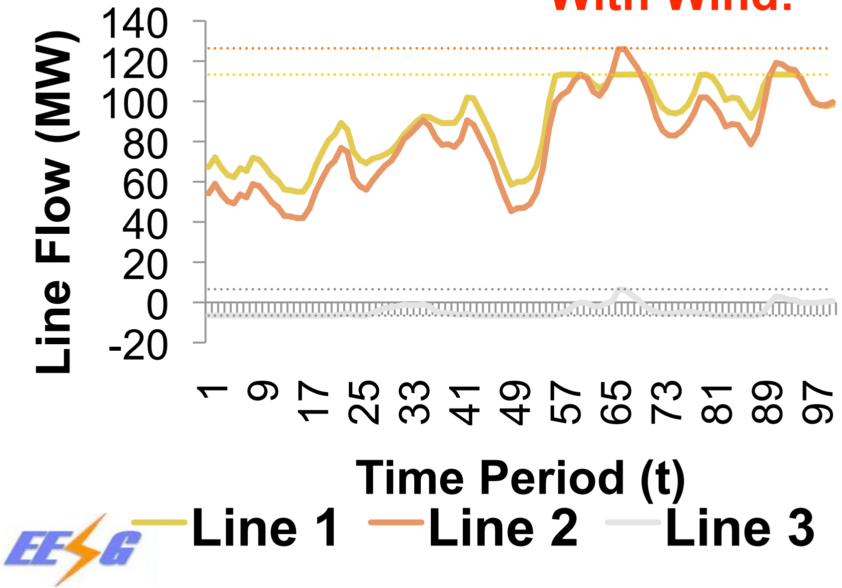
Line Flows With and Without Wind

Without Wind:



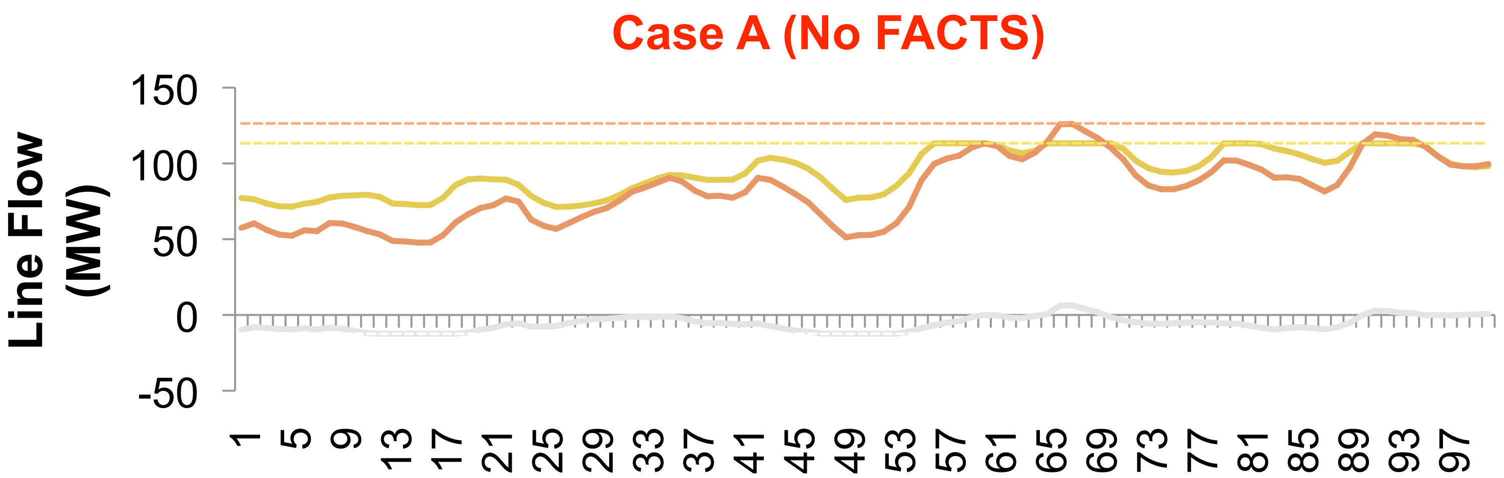
	Line 1	Line 2	Line 3
Average Capacity Utilization Rate	91.8%	91.2%	92.6%
Number of Times the Maximum Capacity is Used	41	31	42

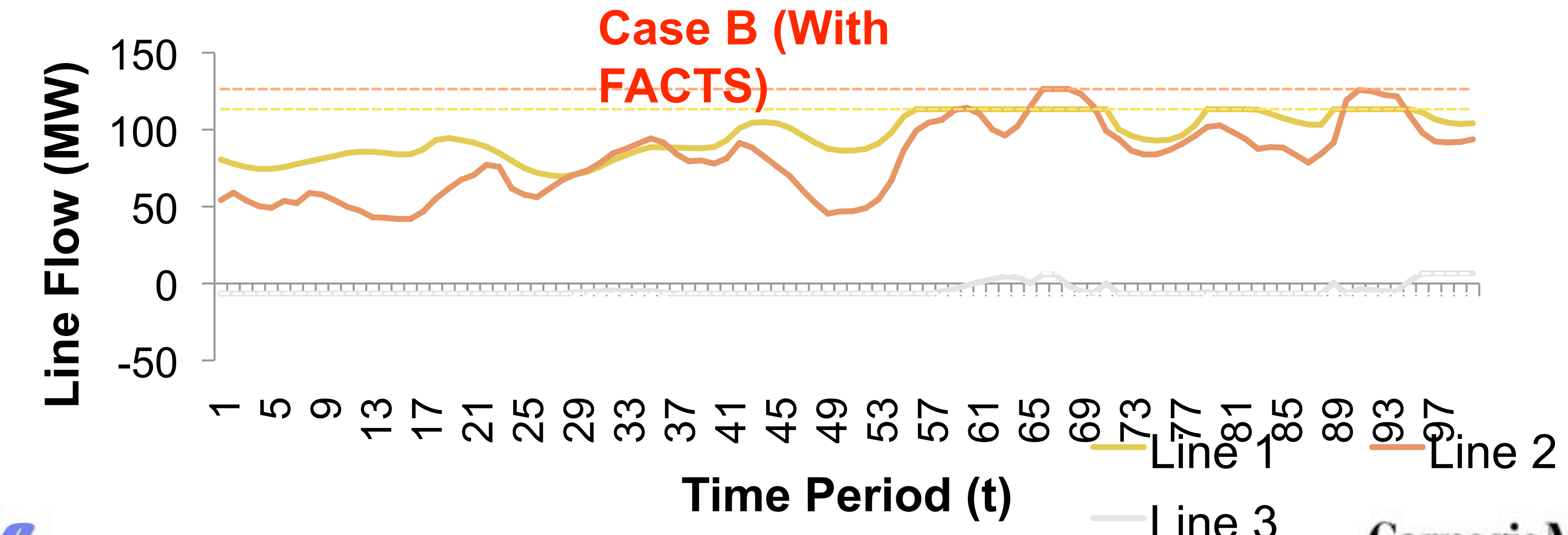
With Wind:



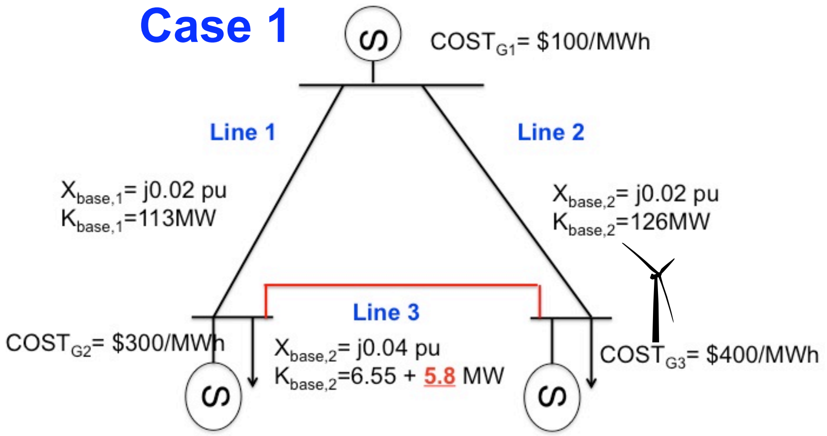
	Line 1	Line 2	Line 3
Average Capacity Utilization Rate	78.9%	64.1%	71.9%
Number of Times the Maximum Capacity is Used	16	4	43

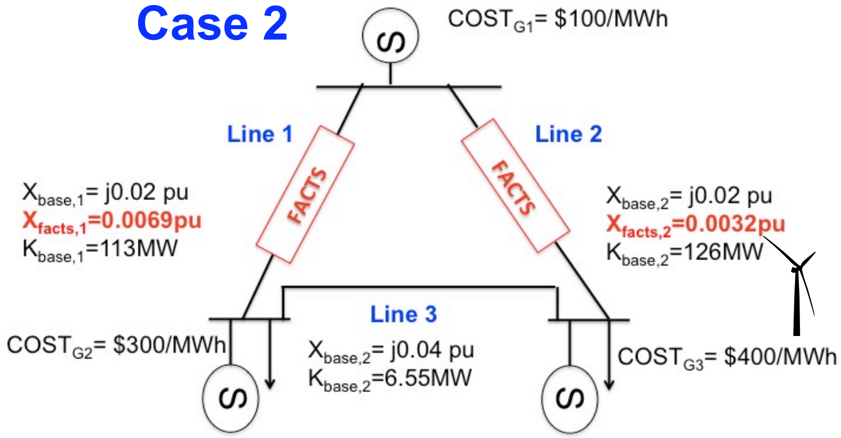
Line Flows for Case A and Case B





Case Study





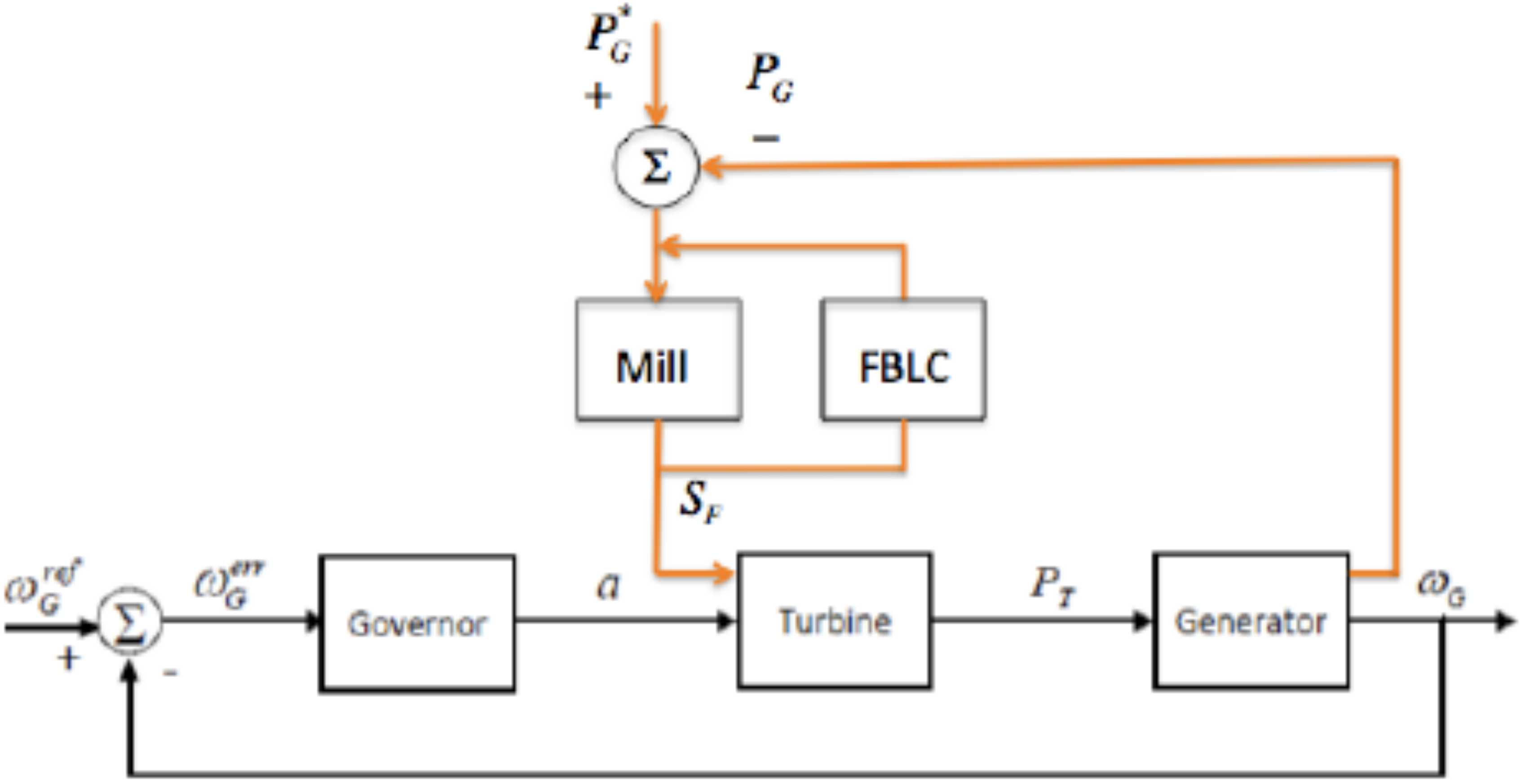
	Base Case with Wind	Case 1	Case 2
Investment Decision		Additional Capacity in Line 3	TCSC in Line 1 and Line 2
Operational Cost (Million $)	1.95	1.82	1.80
Investment Cost (Thousand $)	-	58.1	20.2
Total Cost (Million $)	1.95	1.88	1.82
Average Capacity Utilization Rate	71.7%	66.5%	79.3%
Number of Time Periods in which More Expensive Generators have to be Used	62	30	14

FACTS devices could potentially reduce total investment and operational cost, increase the capacity utilization rate of existing line capacity, and reduce the need for investment in new line capacity by increasing flexibility in the transmission grid.

The value of nonlinear energy conversion control

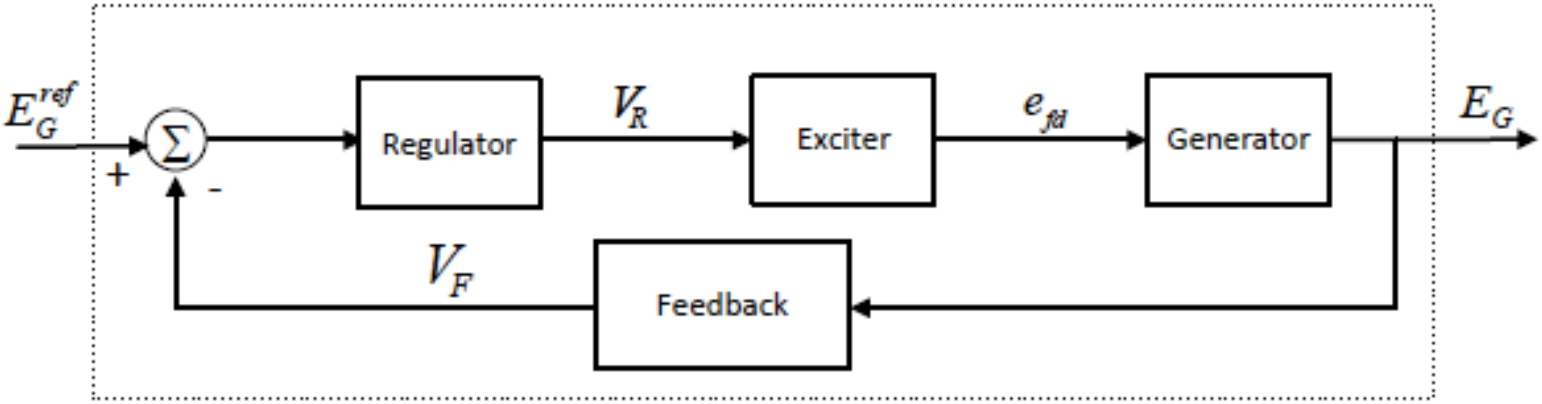
- Work by Astrom at all
- Makes the I-O characteristics of energy conversion process a smooth function

Power plant dynamics and its local control



Value of nonlinear generator control-closed-loop linear (easy to make robust) [31]

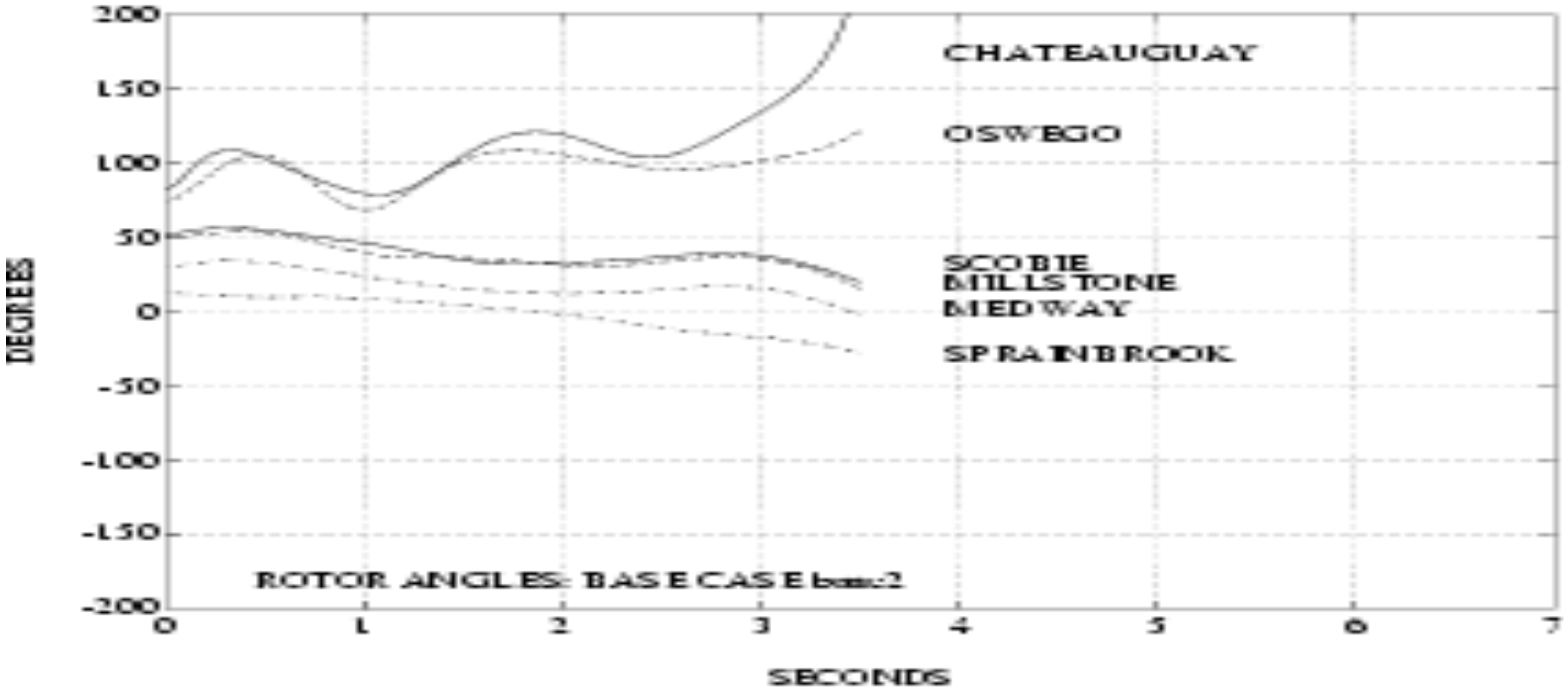
- Conventional power system stabilizer controls DC excitation Efd of the rotor winding in response to omega and E
- FBLC-based Efd control responds to acceleration



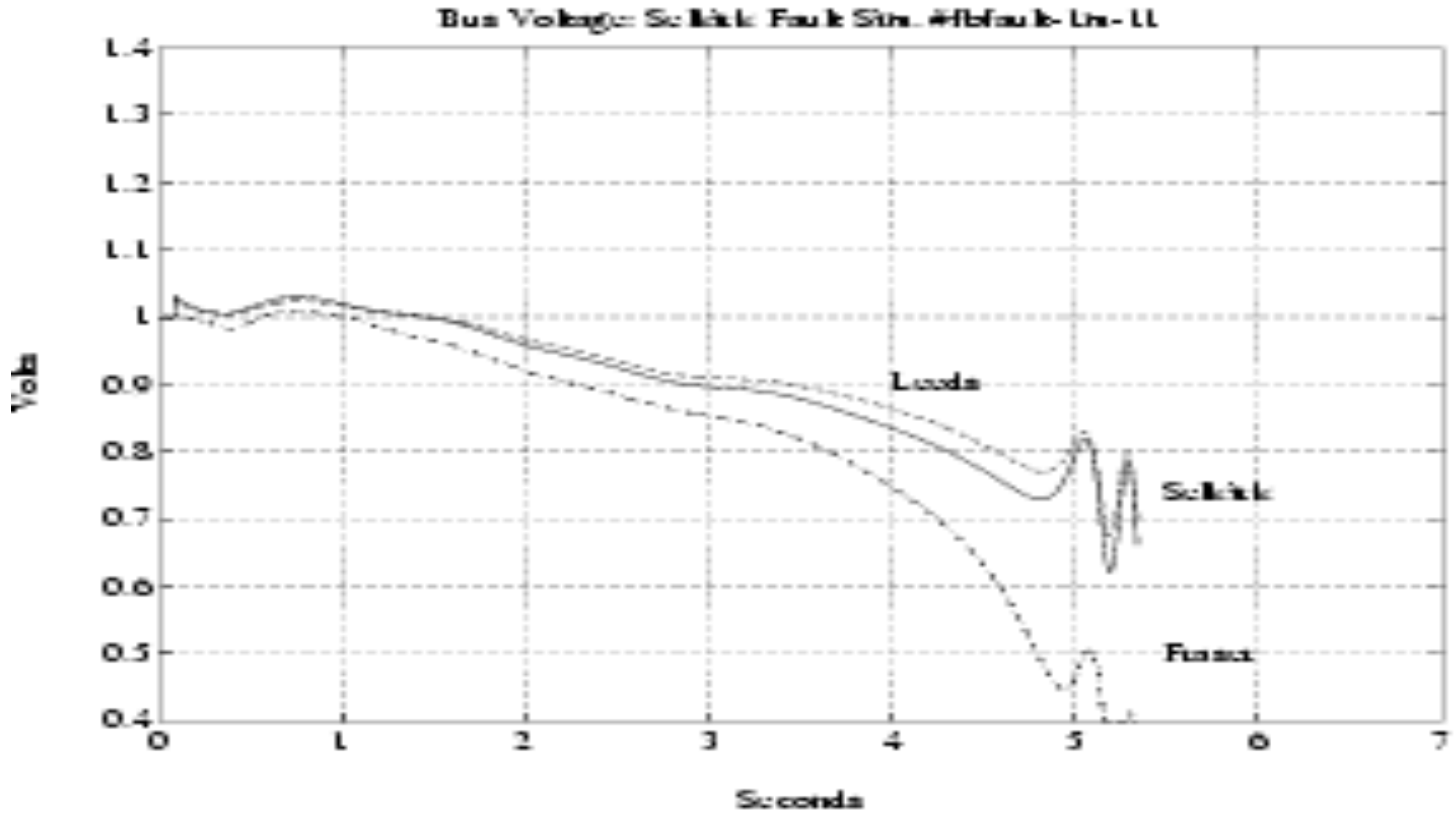
The role of FBLC control in preventing blackouts [13,32]

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

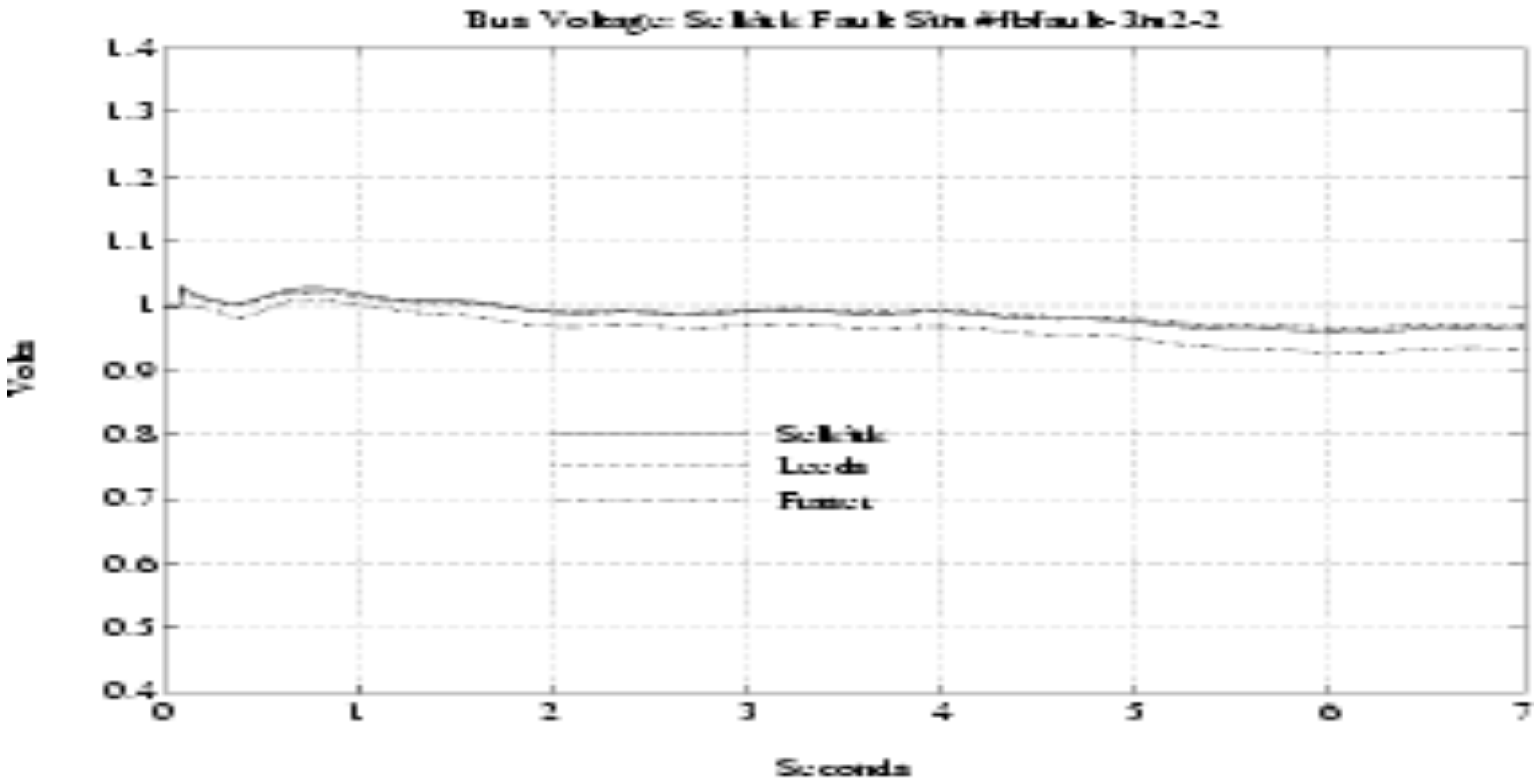
Rotor angles -- base case for Selkrik fault with conventional controller



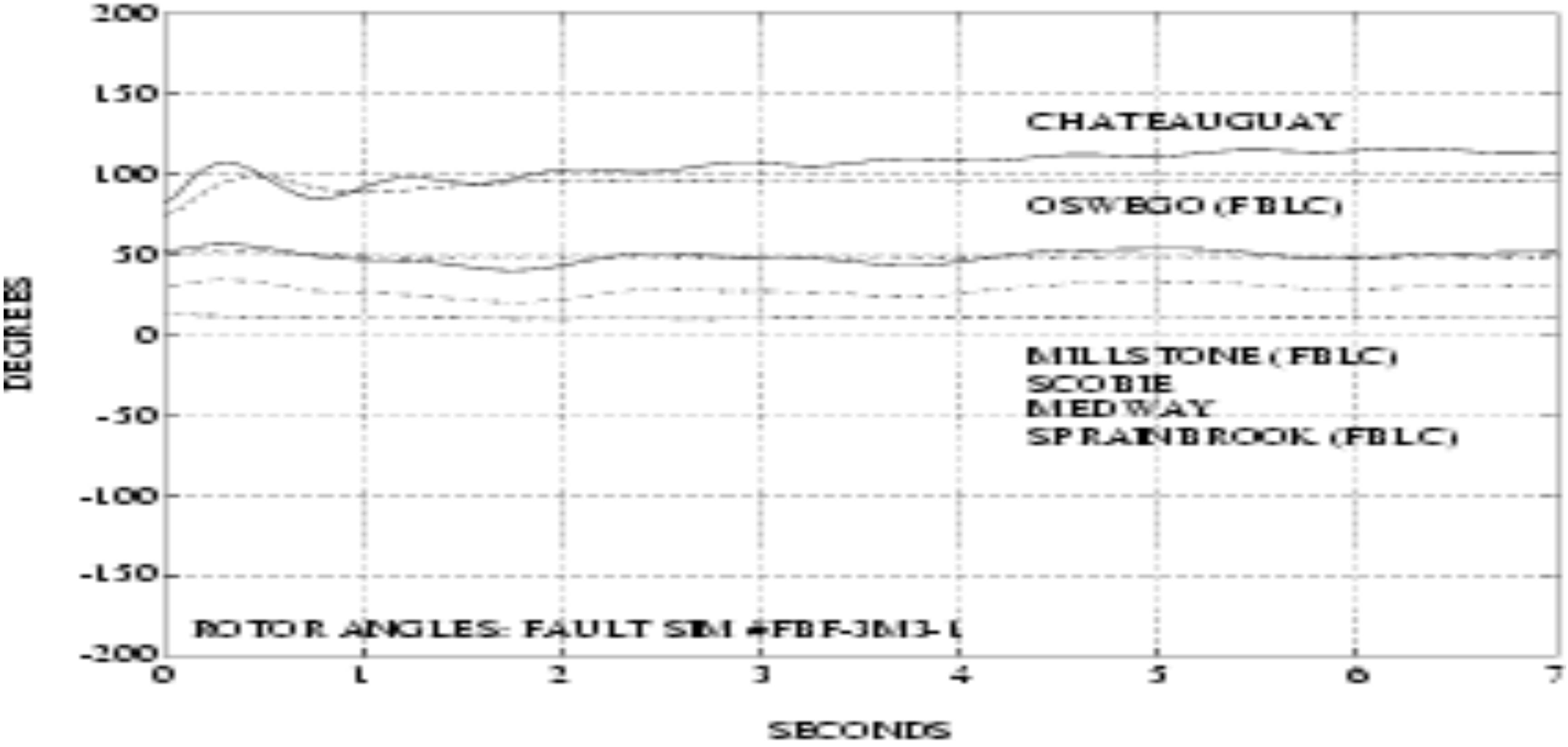
Voltage response with conventional controllers-base case Selkrik fault



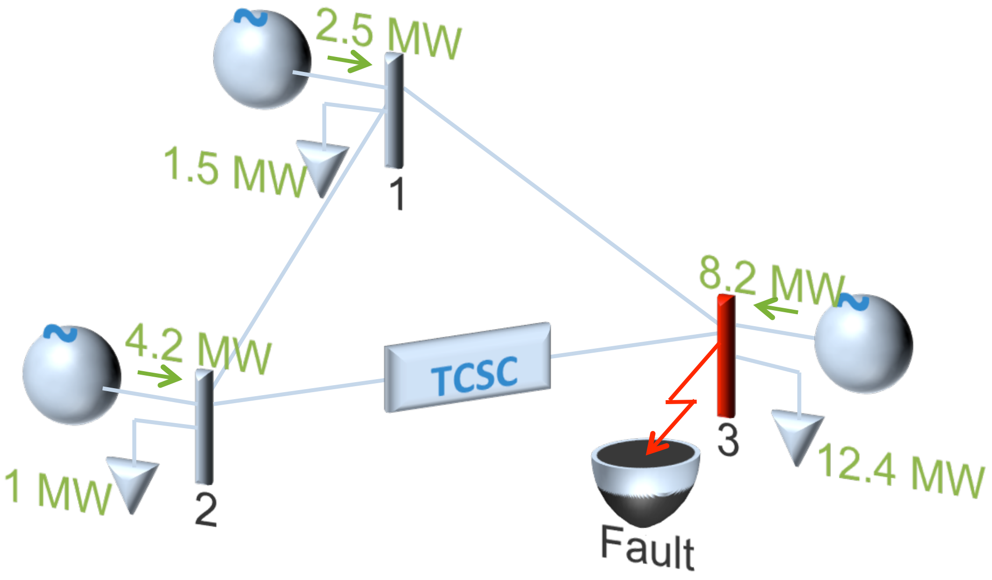
Bus voltages with new controllers



Rotor angle response with local nonlinear controllers--an early example of flat control design



Nonlinear control for storage devices (FACTS,flywheels) [22-25]



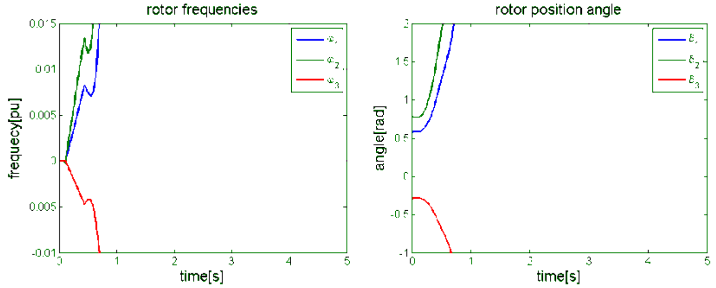
Fault:

- a short circuit at Bus 3
- created at $t = 0.1s$
- cleared at $t = 0.43s$

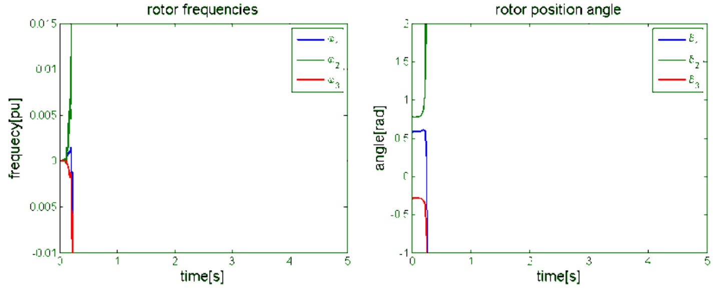
Critical clearing time:

$$T_{CCT} = 0.25s$$

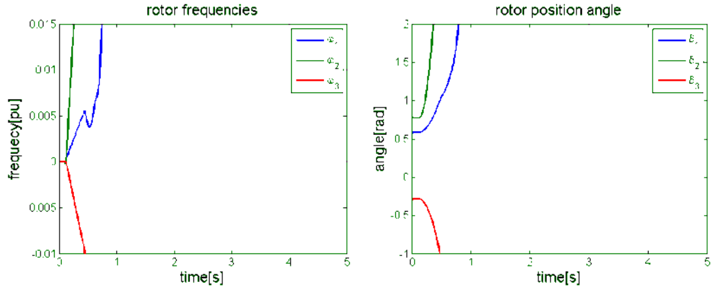
No controller on TCSC



Linear PI power controller[2]



Nonlinear Lyapunov controller[3]



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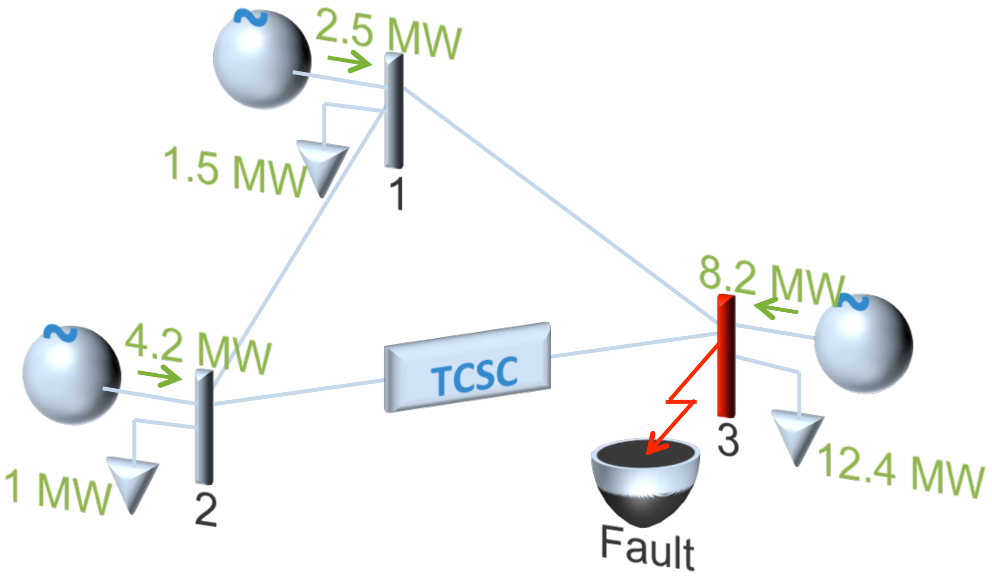
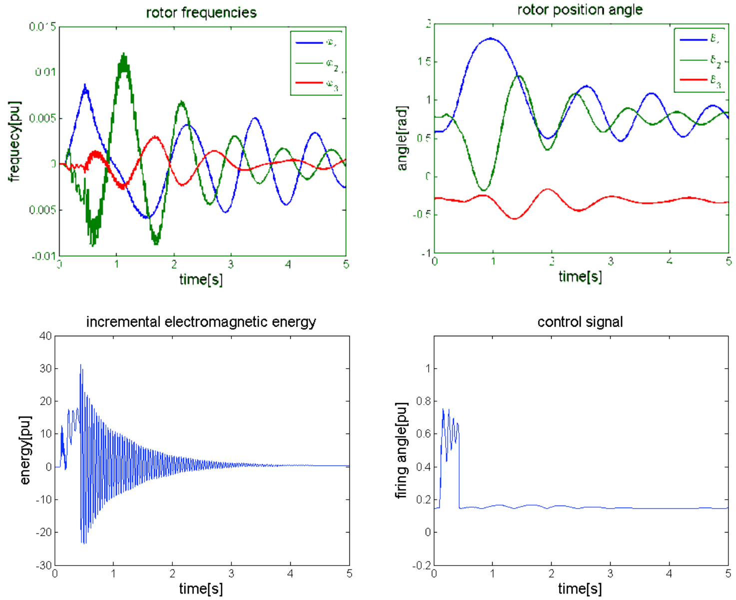
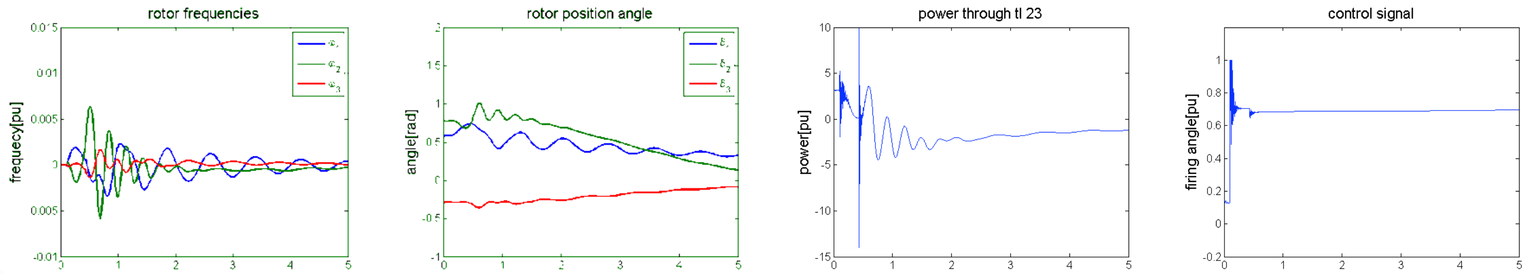
Use of interaction variables in strongly coupled systems



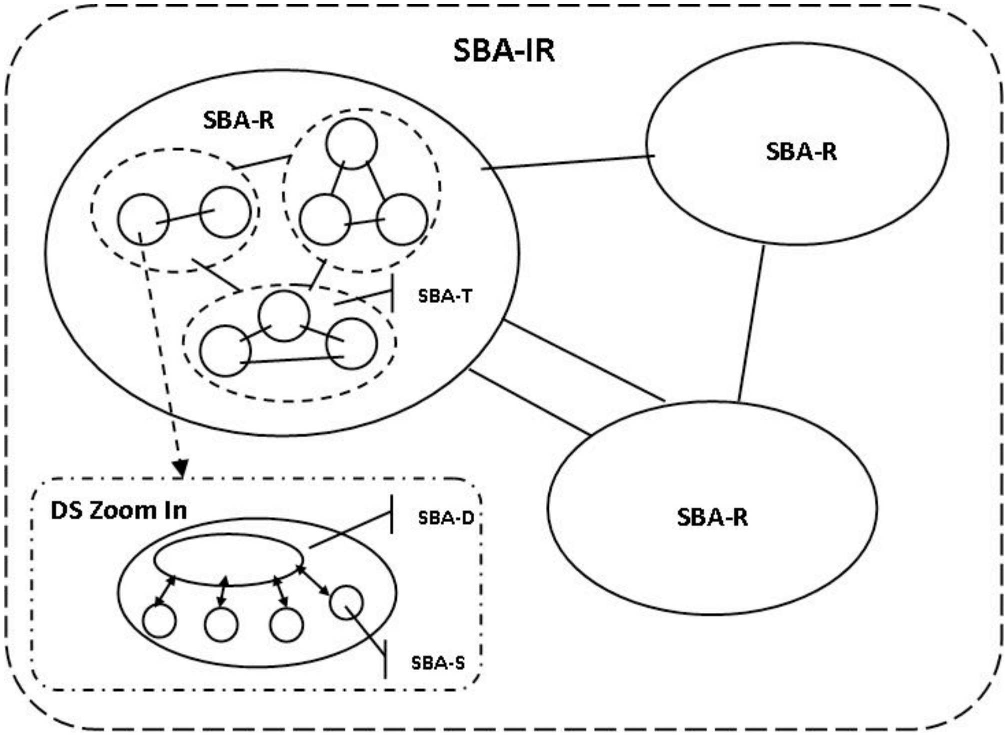
Interaction variable choice 1:



Interaction variable choice 2:



Physics/Model Based Spatial Scaling Up



- **SBA**: Smart Balancing Authorities (Generalization of **Control Area**)
- **IR**: Inter-Region
- **R**: Region
- **T**: Tertiary
- **D**: Distribution
- **S**: Smart Component
- **The actual number of layers depends on needs/ technologies available/ electrical characteristics of the grid**

CONFLICTING OBJECTIVES—COMPLEXITY AND COST OF COMMUNICATIONS VS. COMPLEXITY AND COST OF SENSORS,CONTROL

``SMART BALANCING AUTHORITY” CREATED IN A BOTTOM-UP WAY (AGREGATION)--DyMonDS;
--COMPARE WITH CONVENTIONAL TOP-DOWN DECOMPOSITION

Concluding remarks

- Integration of new technologies in a sustainable way requires viewing the problem as the complex dynamic network problem
- Technical solution can accommodate distributed decision making with minimal coordination
- Rethinking of policies to support this innovative integration of new technologies required [33-35]. A possible stratum of forward markets with all (T,D, G) participating –effectively DyMonDS-based [33,34].

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