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Electric Energy Systems Group

Electrical & Computer ENGINEERING

Toward Reliable and Efficient Resource Management: A Ramp-Rate Limited AC OPF for Integrating Renewable Resources and Responsive Demand

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NETSS

Outline

- **Key challenges to reliable and efficient integration of renewable resources and responsive demand**

- **State of the art solution: DYMONDS-based DC OPF [1]**
  - Internalizing the ramp-rate limits into bids (DYMONDS)
  - integration of DYMONDS and DC OPF

- **Proposed approach: Integrate DYMONDS into AC OPF.**
  --reliability/efficiency coordination using multiple criteria in AC OPF [2-7]
  --illustration of using AC OPF for ensuring reliable and efficient NY and NE grid delivery; multiple performance metrics

- Preliminary conclusions and open questions

Key challenge

- Managing both ramp-rate limits and optimizing voltages in a complex power grid

  --needed to integrate renewable resources

  --very tough computational problem

- Nonlinear optimization using AC OPF –computationally tested on very large systems; for several performance objectives relevant for reliable and efficient resource management [3,4]

- Ramp-rate limited DC OPF for integrating wind power and responsive demand –proof of concept shown [1,2]; dynamic monitoring and decision systems (DYMONDS) concept [5].

- Key new question: Can one combine the two near-optimally?

Nonlinear optimization using AC OPF

- Today' operating and planning practice: Reliability ensured by extensive power flow-based analyses
- Very little reliance on corrective adjustments of available resources as operating conditions change
- Real power scheduled to meet forecast demand
- Voltage-controllable equipment is generally not adjusted when real power is scheduled
- Both reliability and efficiency can be significantly improved if voltage is optimized on generators, controllable transformers, capacitor banks and FACTS

Corrective Resource Management—key to managing intermittency [6]

- Adjust resources as conditions change to guarantee ``all the time'' while maximizing efficiency and minimizing pollution to the extent possible.
- Must operate resources within their limits:
  - thermal and voltage equipment limits.
  - system delivery (voltage and stability) limits.
- The best performance is obtained by adjusting the most resources.

Multiple Performance Objectives [6]

Reliability

- Maintaining compact voltage profile
- Serving the greatest load
- Responding to contingencies and intermittent resources
- Balancing power flow and maintaining operation within the limits

Efficiency

- Economic dispatching
- Reducing volatility of electricity prices
- Enabling most economical transactions
- Eliminating conservative proxy transfer limits
- Avoiding Reliability Must Run (RMR) rules
- Implementing responsive demand
- Loss minimization

Effects of voltage control on efficiency in NE [3]

	No control	P_G	P_G, V_G	$P_G, Taps$	$P_G, V_G, Taps$
Base Case	$ 688,092	–	–	–	–
Normal Operation	–	$ 612,669	$ 605,135	$ 606,712	$ 604,391
Worst Case $(N-2)$ Contingency	–	not feasible	$ 618,731	not feasible	$ 614,233

TABLE I

ECONOMIC DISPATCH OUTCOMES AS A RESULT OF VOLTAGE OPTIMIZATION USED

Reliability first, efficiency second

- ISO-NE sends to the owners of voltage controllable equipment anticipated power demand and generation.
- The equipment owners perform MXV with respect to the controls $(V_G, Taps)$ only. This optimization results in the acceptable voltage ranges bounded by upper and lower triangle symbols in Figure 2. The controlled equipment is frozen at the optimal values. The range of acceptable voltages and the optimized $(V_G, Taps)$ are passed on to the ISO.
- The ISO-NE optimizes its real power generation P_G to minimize the total generation cost within the ranges of voltages and for the optimized $(V_G, Taps)$ given by the equipment owners.

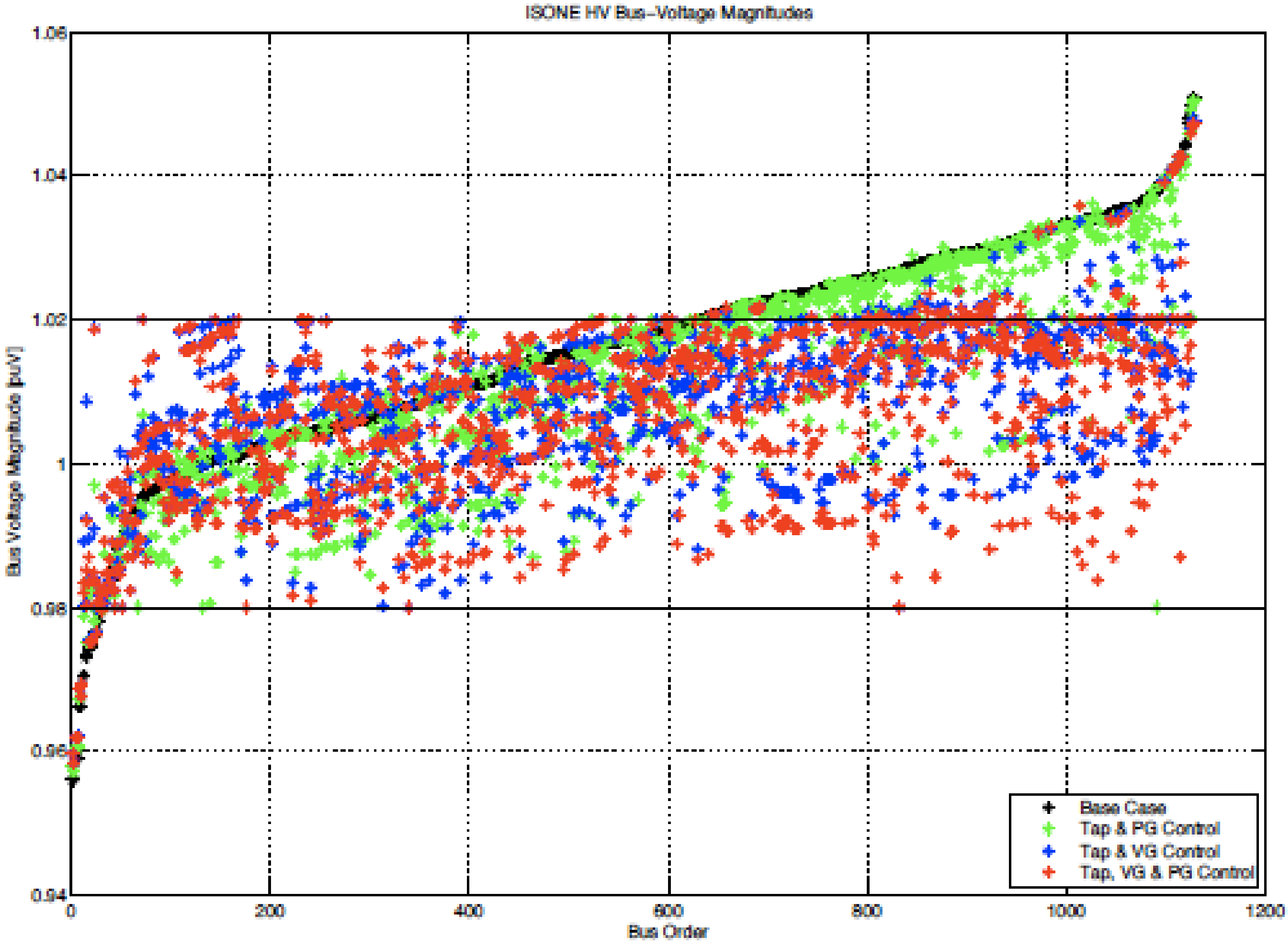


Fig. 1. Dependence of Voltage Profile on the Type of Controllable Equipment Following MXV Runs in HV NE Power System

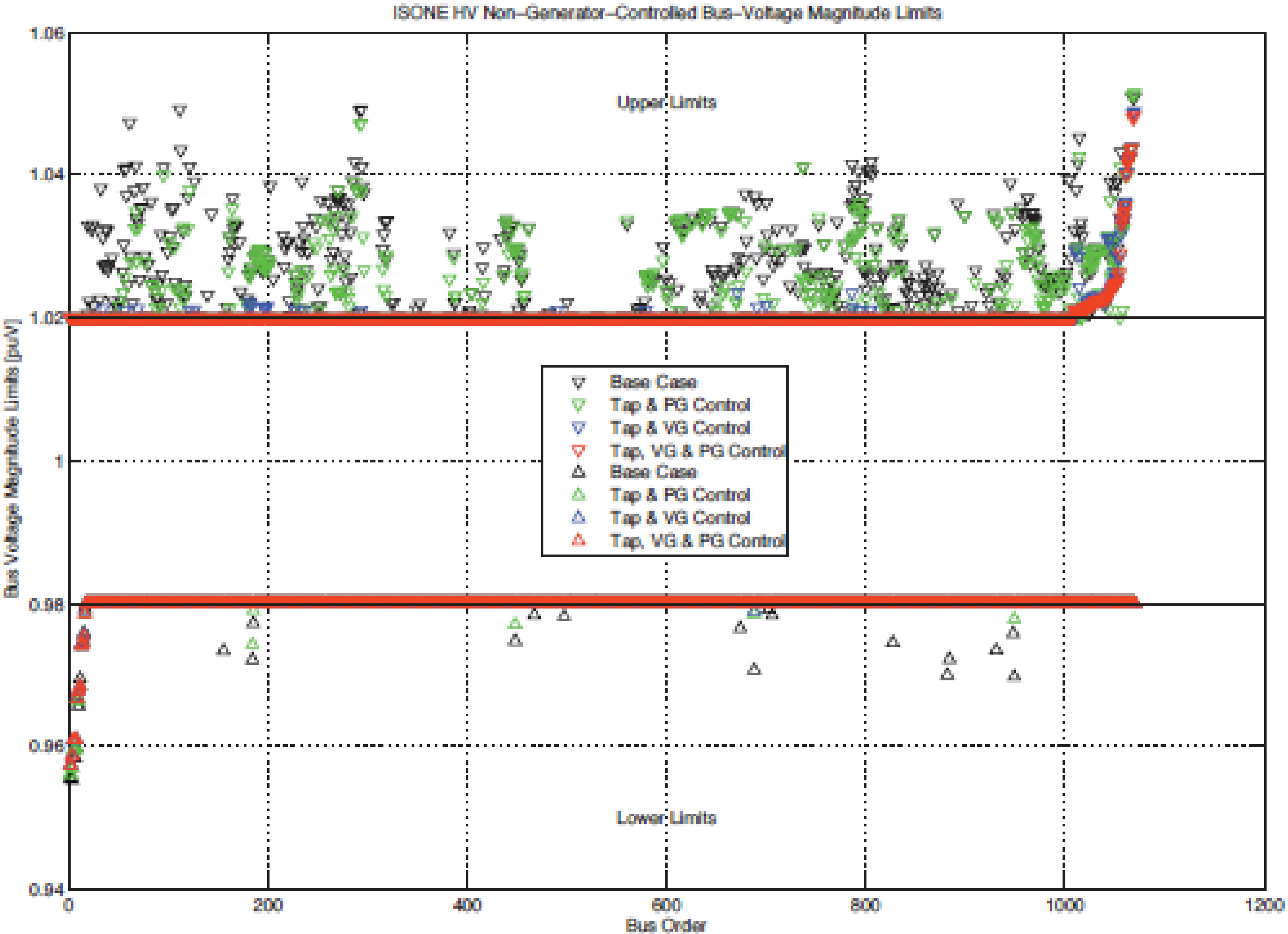


Fig. 2. Best possible ranges of permissible voltages obtained using MXV

Reconciling reliability and efficiency

- Assuming perfect information by the ISO-NE, a centralized AC OPF performed subject to all constraints

  --Step 1 The most reliable voltage profile using Minimize Extreme Voltage (MXV) shown in Figure 2.

  -Step 2 Re-optimize real power while maintaining voltage within the most reliable limits

****THE COST OF RELIABILITY : DIFFERENCE BETWEEN**

--generation cost resulting from performing Steps 1 and 2 ($643,848); and,

--generation cost obtained using single optimization of both real power and voltage subject to 0.98-1.02pu constraints ($604,391)**

Interdependence of reliability and efficiency

Contingency?	Voltage Range	Thermal Limit	Generation Cost [$/Hr.]	Generation Cost Increase
No	0.98-1.02	Rate A (Normal)	1,110,290	Benchmark
Yes	0.98-1.02	Rate A	1,145,554	3.2%
Yes	0.95-1.05	Rate A	1,120,197	0.9%
Yes	0.98-1.02	Rate B (LTE)	1,114,792	0.4%
Yes	0.95-1.05	Rate B	1,080,022	-2.7%

Fig. 3. Effects of Voltage Limits on Generation Cost During A Severe Contingency

Potential reliability/efficiency coordination in NYCA

- Different dispatch needed for implementing the most economic dispatch than for delivering most power to NYC [5]
- Thermal limits are less pronounced than voltage-related limits
- There exist voltage-related operating constraints to

  --the most economic dispatch

  --delivering clean hydro power from Canada to NYC

  --transferring large amount of power across Central-East interface

  --wind power will make the delivery even more challenging

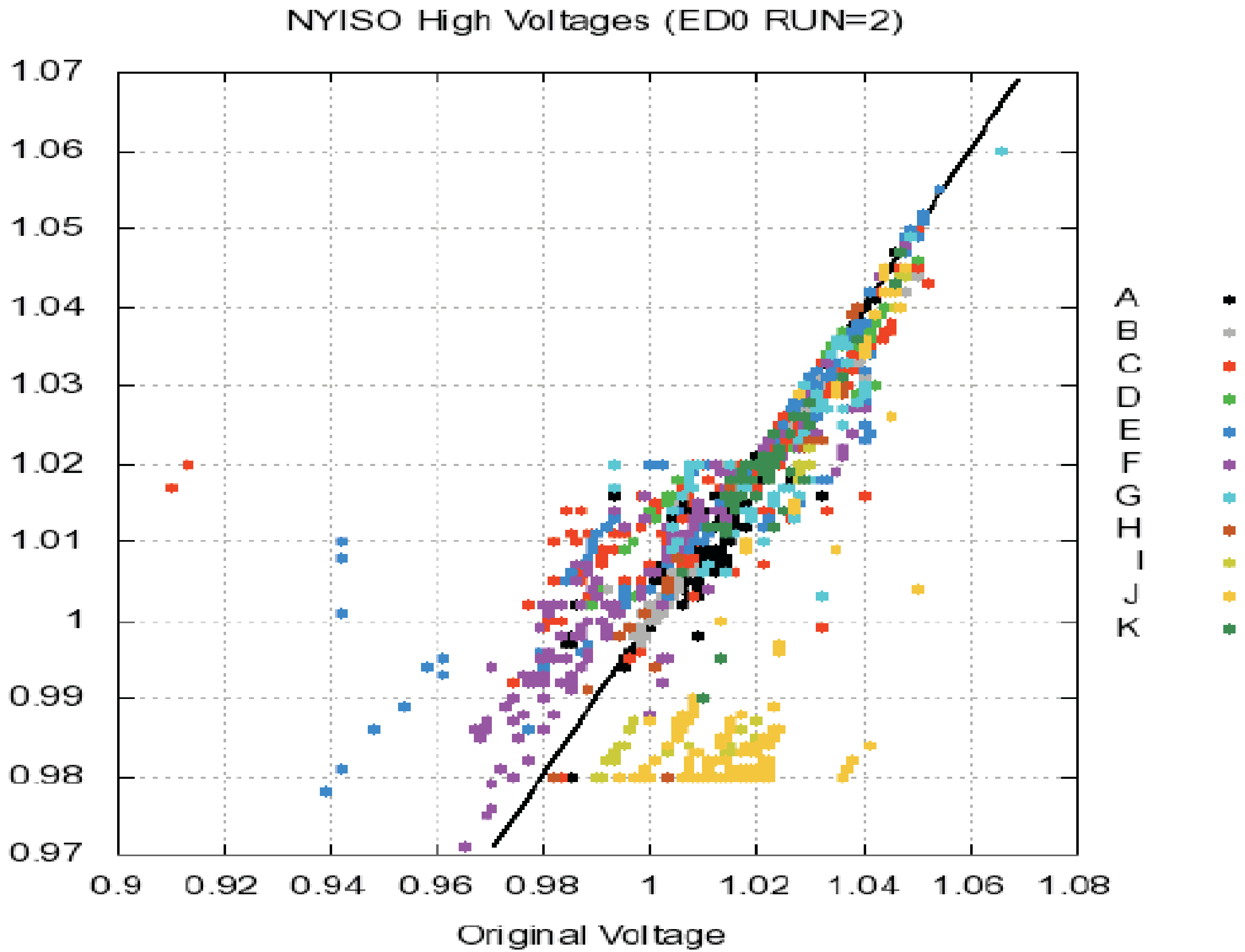


Fig. 4. Comparison of the Base Case and Optimized Voltage by Adjusting AVRs for economic Dispatch

Run Set		Run 0		Run 2		Run 7	
		NYC Load [MW]	Int. Flow [MW]	NYC Load [MW]	Int. Flow [MW]	NYC Load [MW]	Int. Flow [MW]
DE /WC	L2	21156	DE: 2285 WC: 966	21542	DE: 2798 WC: 1438	21594	DE: 2800 WC: 1441
	PP[DEWC]3	20122	DE: 2154 WC: 846	20175	DE: 2203 WC: 900	20242	DE: 2203 WC: 902
	IF[DE]1	20546	2388	20867	2812	20553	2812
	IF[WC]1	20581	1059	21016	1453	20630	1457
CE	L5	21381	3109	21509	3207	21538	3209
	PP[CE]2	20762	3027	21114	3248	21332	3292
	IF[CE]1	21116	3398	21235	3482	21193	3515

Fig. 5. A comparison of NYC Load and Interface Flows Across Various Optimizations

Management of inter-temporal constraints under uncertainties –the problem of ramp-rates [1,5,7]

- Conventional system operation
  - Centralized decision making
    - ISO knows and decides all
  - Not proper for future electric energy systems
    - Too many heterogeneous decision making components : DGs, DRs, electric vehicles, LSEs, etc.

- Dynamic Monitoring Decision-making System (DYMONDS)
  - Distributed decision making system
    - Distributed optimization of multiple components → computationally feasible
  - Individual decisions submitted to ISO (as supply/demand bids)
    - Individual inter-temporal constraints **internalized**
    - Market clearance and overall system balanced by ISO

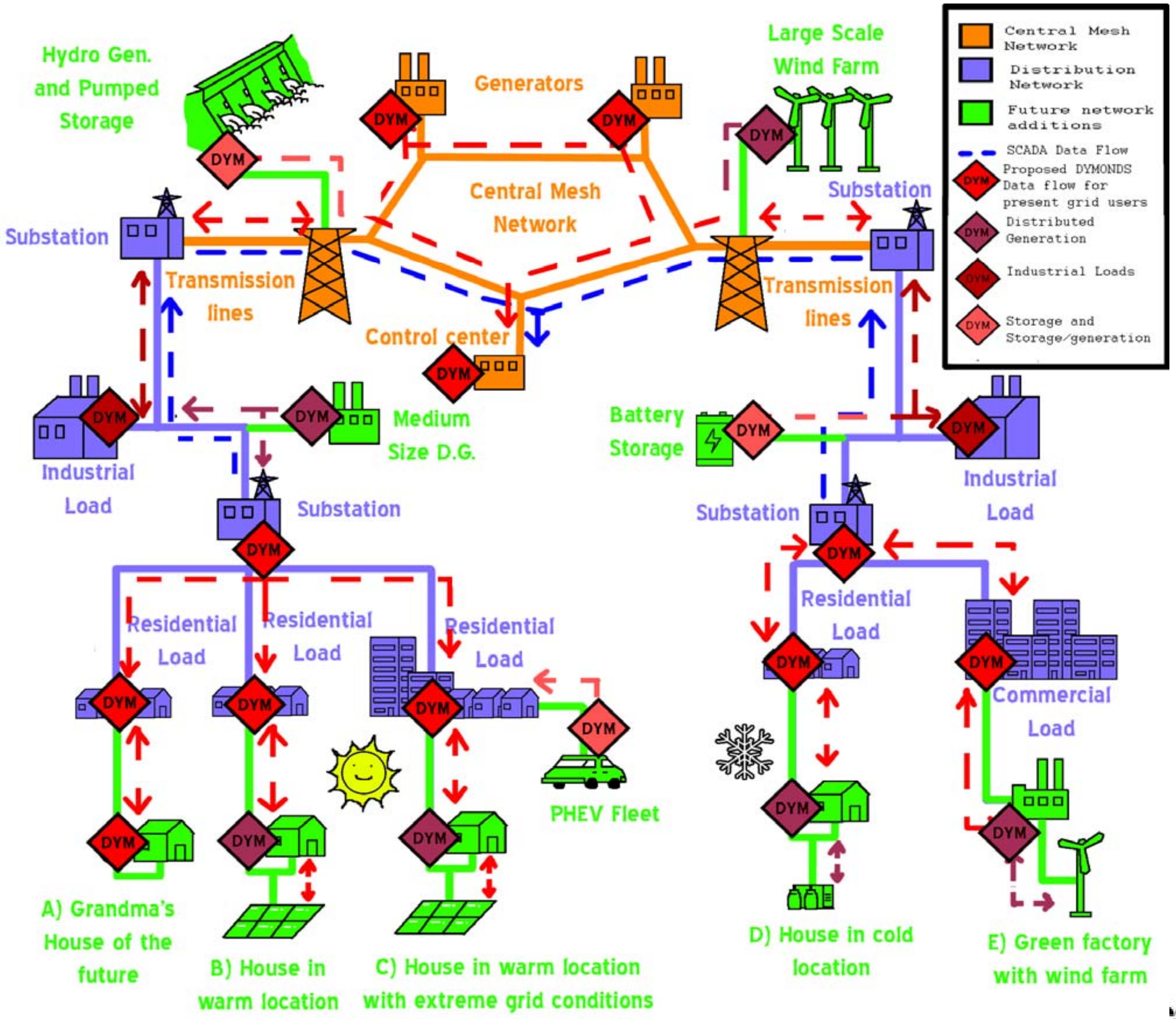
Managing wind power—smarter way

- Actively control the output of available intermittent resources to follow the trend of time-varying loads.
- By doing so, the need for expensive fast-start fossil fuel units is reduced. Part of the load following is done via intermittent renewable generation.
- The technique used for implementing this approach is called model predictive control (MPC).
- Implicit value of storage

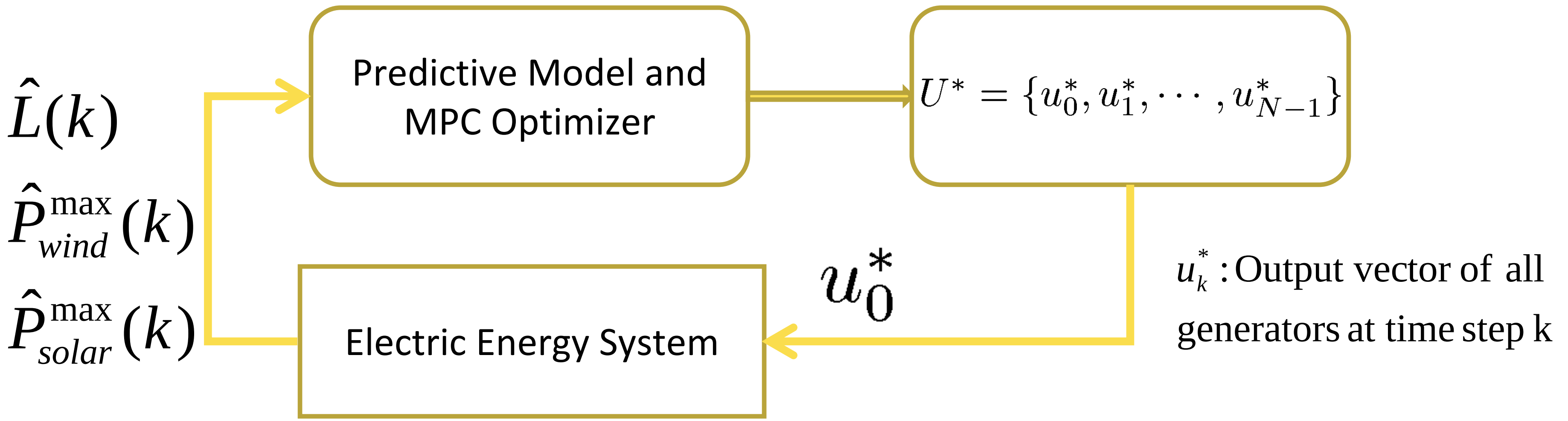
Basic idea of minimally coordinated self-dispatch—DYMONDS

- Distributed management of temporal interactions
- Different technologies perform look-ahead decision making given their unique temporal and spatial characteristics and system signal (price or system net demand); they create bids and are cleared by the layers of coordinators
- Putting Auctions to Work in Future Energy Systems
- We illustrate next a supply-demand balancing process in an energy system with wind, solar, conventional generation, elastic demand, and PHEVs.

DYMONDS-enabled Physical Grid [5]



Centralized MPC –Benchmark [1]



- 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.

Problem 3A: Centralized MPC-based Dispatch with Inelastic Demand

$$\text{Solve} : \min_{P_G} \sum_{k=1}^{K} \sum_{i \in G} (C_i(P_{G_i}(k))), i \in G \tag{39}$$

$$s.t. \sum_{i} P_{G_i}(k) = \sum_{z} \hat{L}_z(k), i \in G, z \in Z; \tag{40}$$

$$\hat{L}_z(k) = f_z(L_z(k-1)), z \in Z; \tag{41}$$

$$\hat{P}_{G_j}^{max}(k) = g_j(\hat{P}_{G_j}^{max}(k-1)); \tag{42}$$

$$\hat{P}_{G_j}^{min}(k) = h_j(\hat{P}_{G_j}^{min}(k-1)); \tag{43}$$

$$\hat{P}_{G_j}^{\min} \leq P_{G_j}(k) \leq \hat{P}_{G_j}^{\max}, j \in G_r; \tag{44}$$

$$P_{G_i}^{\min} \leq P_{G_i}(k) \leq P_{G_i}^{\max}, i \in G \setminus G_r; \tag{45}$$

$$|P_{G_i}(k+1) - P_{G_i}(k)| \leq R_i, i \in G; and, \tag{46}$$

$$|F(k)| \leq F^{max}. \tag{47}$$

Problem 3B: Centralized MPC-Based Dispatch with Elastic Load

$$\text{Solve}: \min_{P_G, L} \sum_{k=1}^{K} \left(\sum_{i \in G} (C_i(P_{G_i}(k))) - \sum_{z \in Z} (B_z(L_z(k))) \right), \tag{48}$$

$$s.t. \sum_{i \in G} P_{G_i}(k) = \sum_{z \in Z} L_z(k); \tag{49}$$

$$\hat{P}_{G_r}^{max}(k) = g_j(\hat{P}_{G_r}^{max}(k-1)), r \in G_r; \tag{50}$$

$$\hat{P}_{G_r}^{min}(k) = g_j(\hat{P}_{G_r}^{min}(k-1)), r \in G_r; \tag{51}$$

$$\hat{P}_{G_j}^{\min} \leq P_{G_j}(k) \leq \hat{P}_{G_j}^{\max}, j \in G_r; \tag{52}$$

$$P_{G_i}^{\min} \leq P_{G_i}(k) \leq P_{G_i}^{\max}, i \in G \setminus G_r; \tag{53}$$

$$|P_{G_i}(k+1) - P_{G_i}(k)| \leq R_i, i \in G; and, \tag{54}$$

$$|F(k)| \leq F^{max}. \tag{55}$$

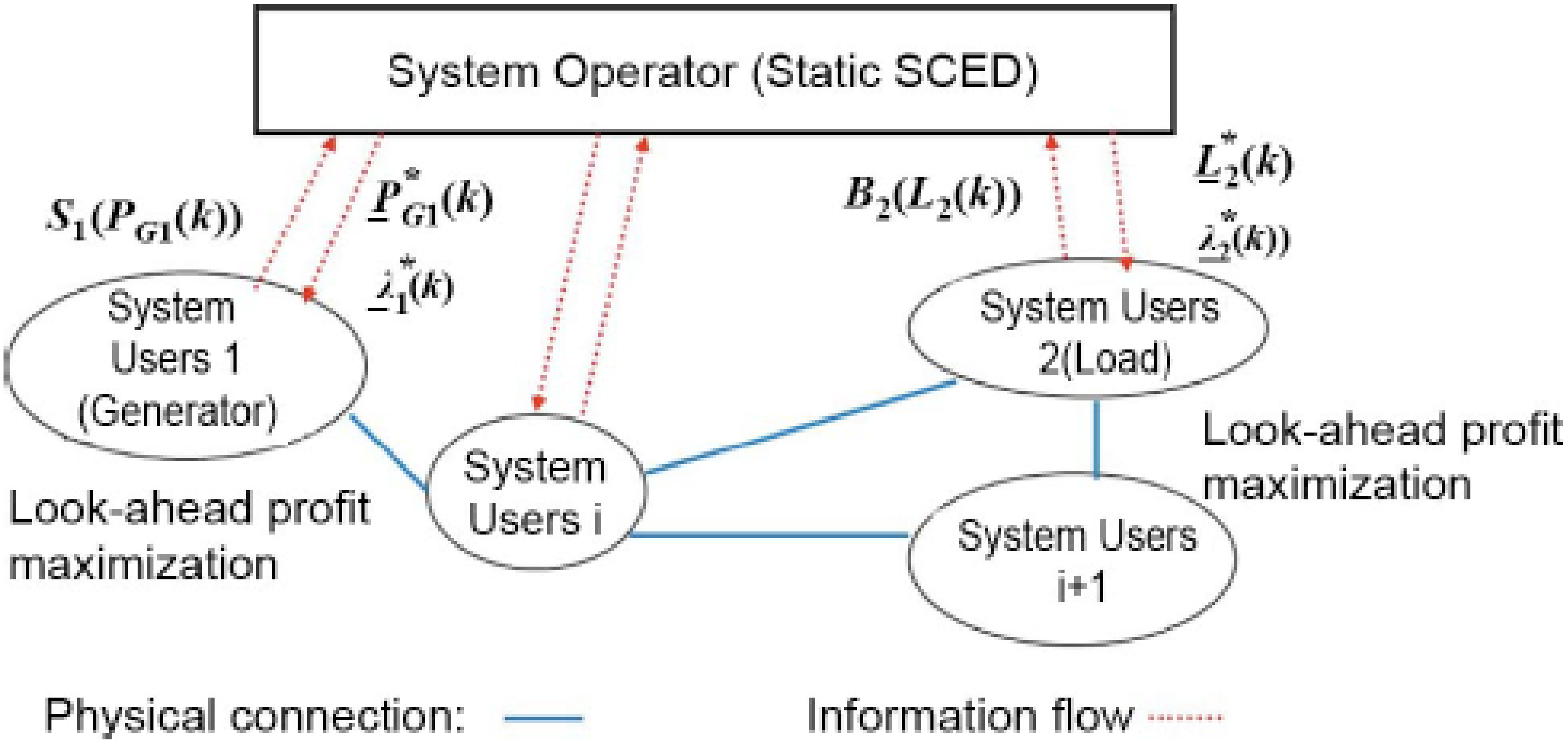


Fig. 3. Required information exchange for DYMONDS-based dispatch.

DYMONDS for MPC-based supply function computation-

Given: $[\hat{\lambda}(k+1) \quad \hat{\lambda}(k+2) \quad \cdots \quad \hat{\lambda}(k+K)]$

$$\text{Solve:} \quad \max_{P_{G_i}(k)} \sum_{k+1}^{k+K} \lambda(\hat{k})(P_{G_i}(k)) - (C_i(P_{G_i}(k))) \quad (44)$$

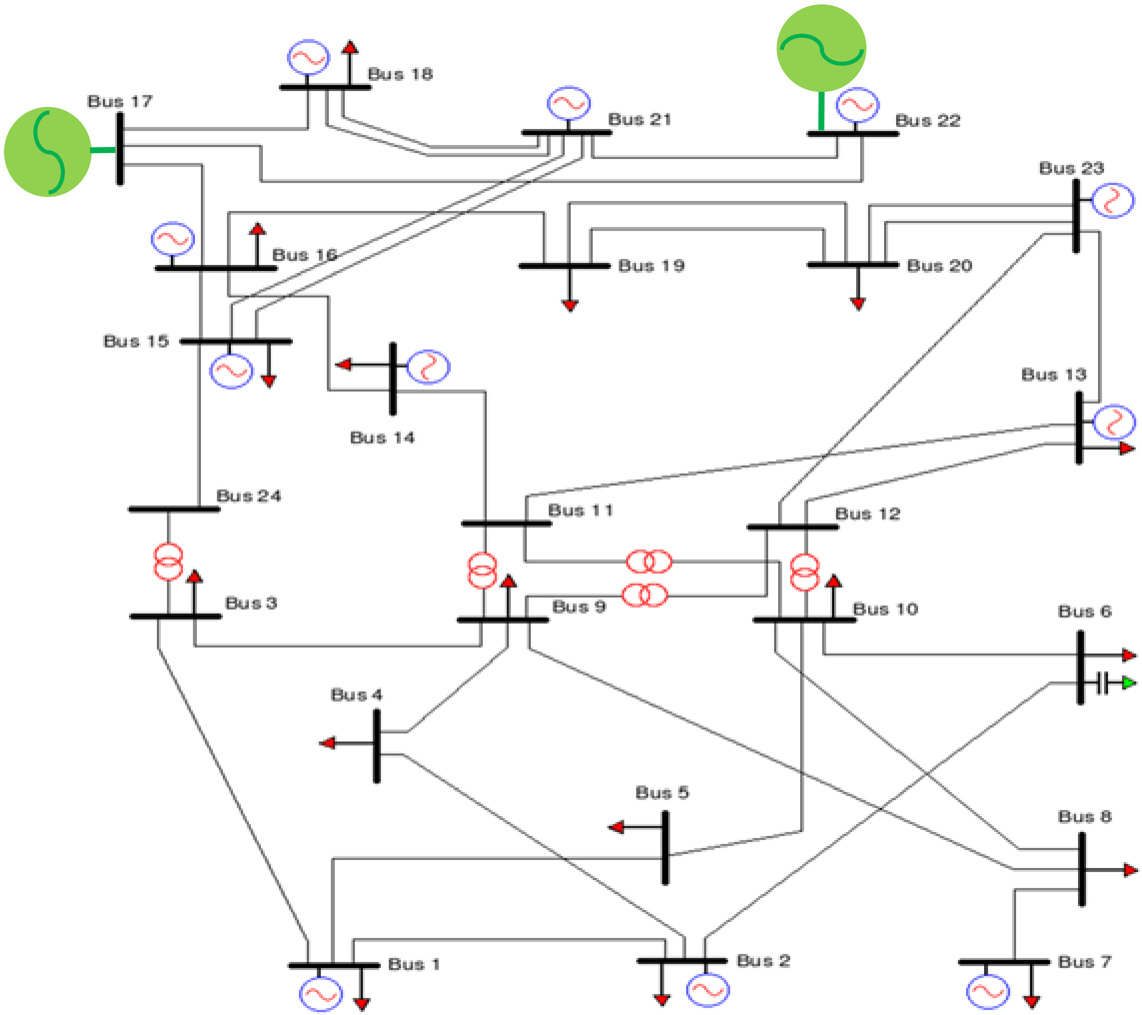
$$\text{s.t.} \quad \hat{P}_{G_i}^{\max}(k) = g_i(\hat{P}_{G_i}^{\max}(k-1)) \quad (45)$$

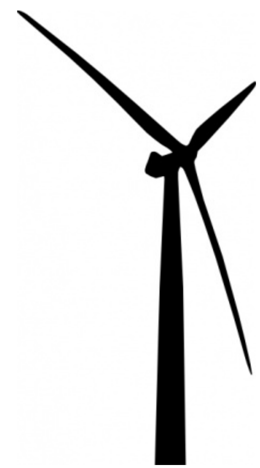
$$\hat{P}_{G_i}^{\min}(k) = h_i(\hat{P}_{G_i}^{\min}(k-1)) \quad (46)$$

$$|P_{G_i}(k+1) - P_{G_i}(k)| \leq R_i \text{ and} \quad (47)$$

$$\hat{P}_{G_i}^{\min} \leq P_{G_i}(k) \leq \hat{P}_{G_i}^{\max}. \quad (48)$$

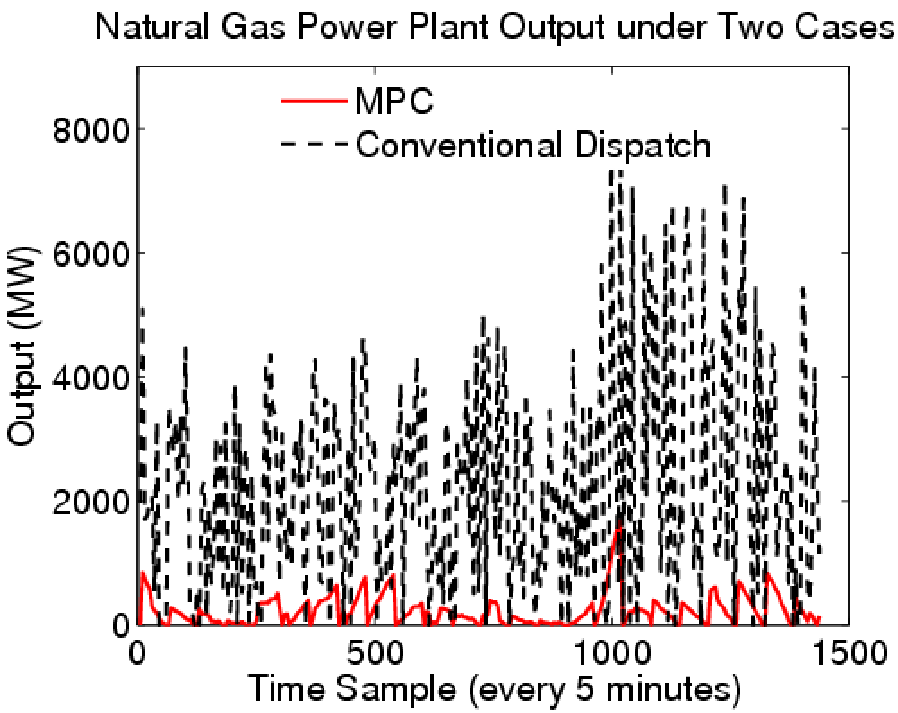
DYMONDS Simulator
IEEE RTS with Wind Power

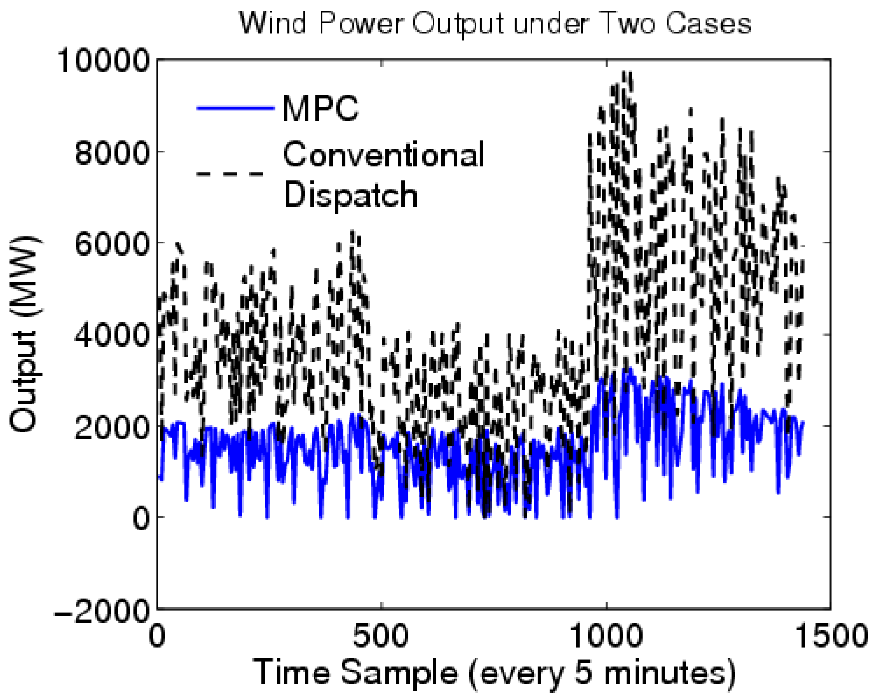




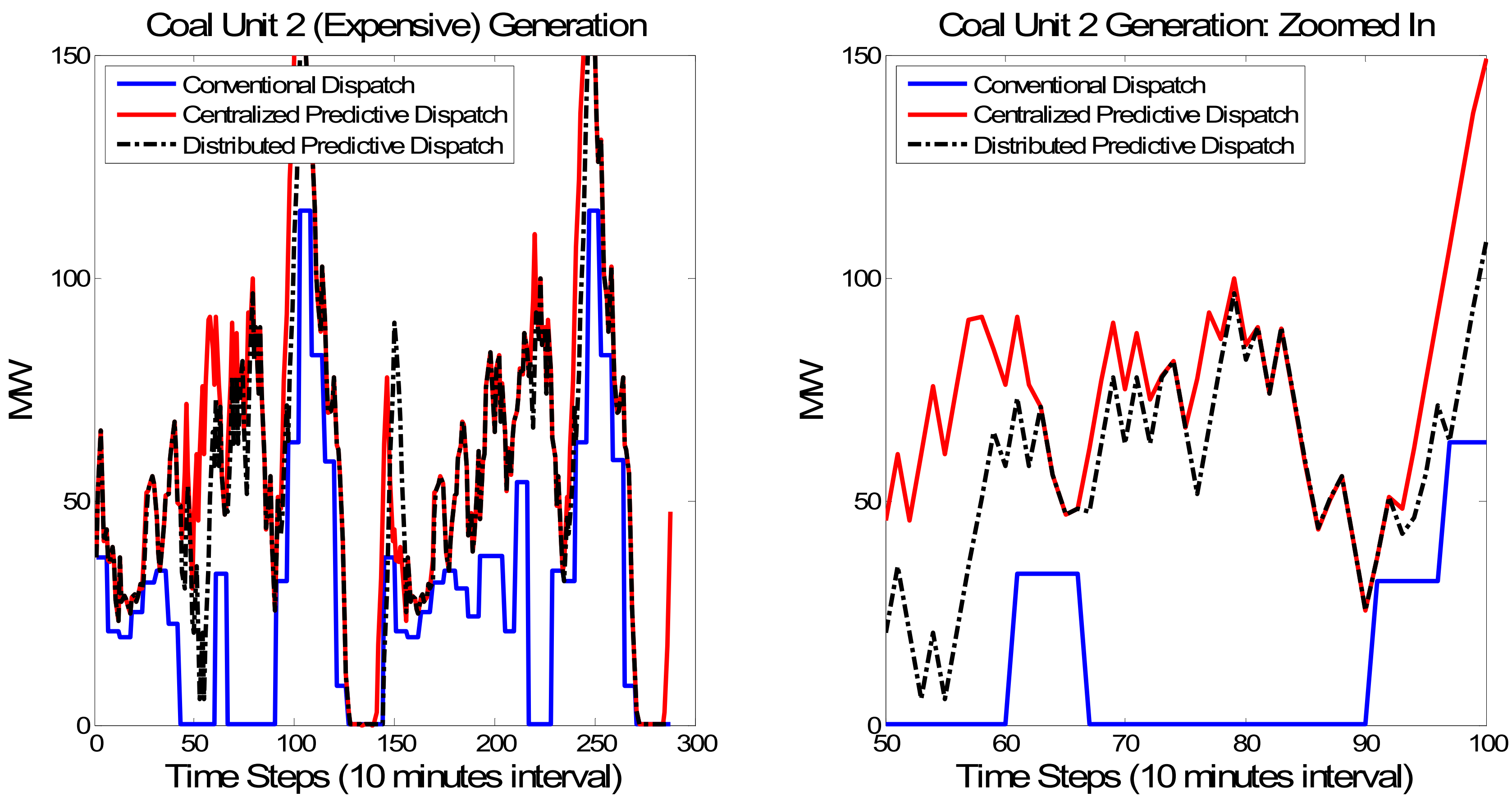
- 20% / 50% penetration to the system [2]

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



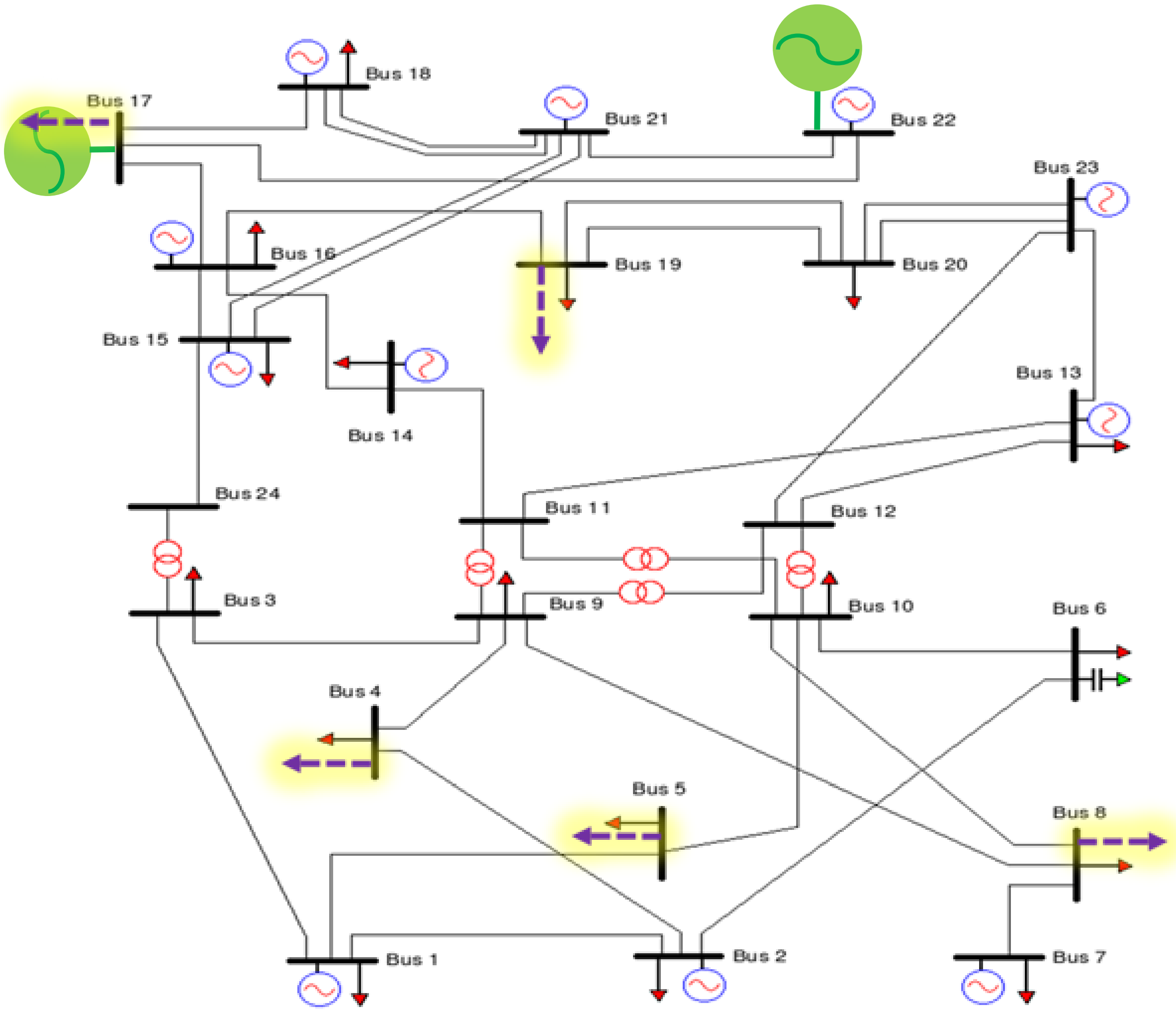


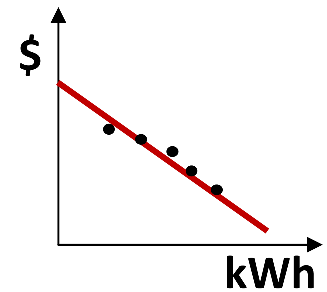
*: load data from New York Independent System Operator, available online at http://www.nyiso.com/public/market_data/load_data.jsp



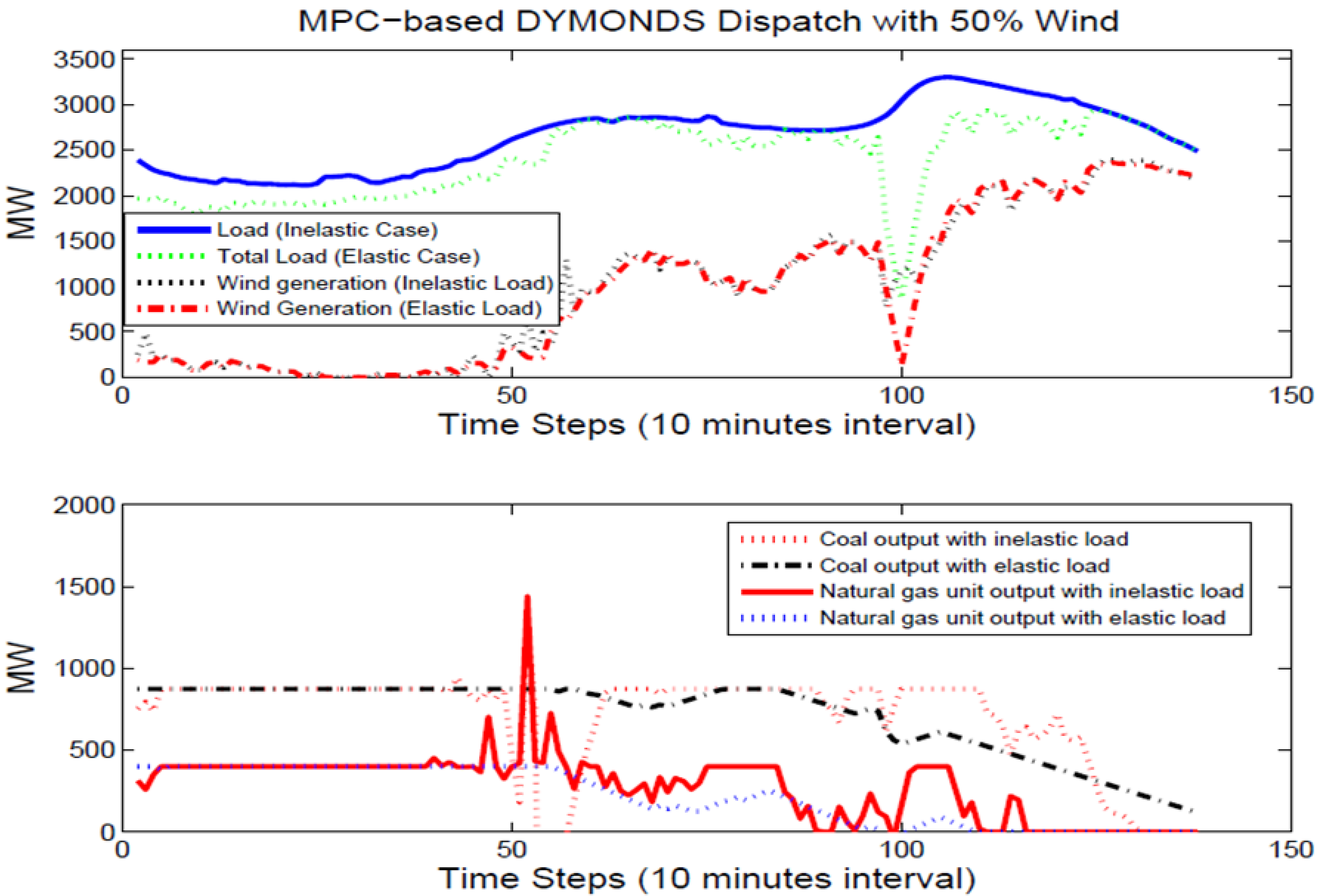
BOTH EFFICIENCY AND RELIABILITY MET

DYMONDS Simulator
Impact of price-responsive demand

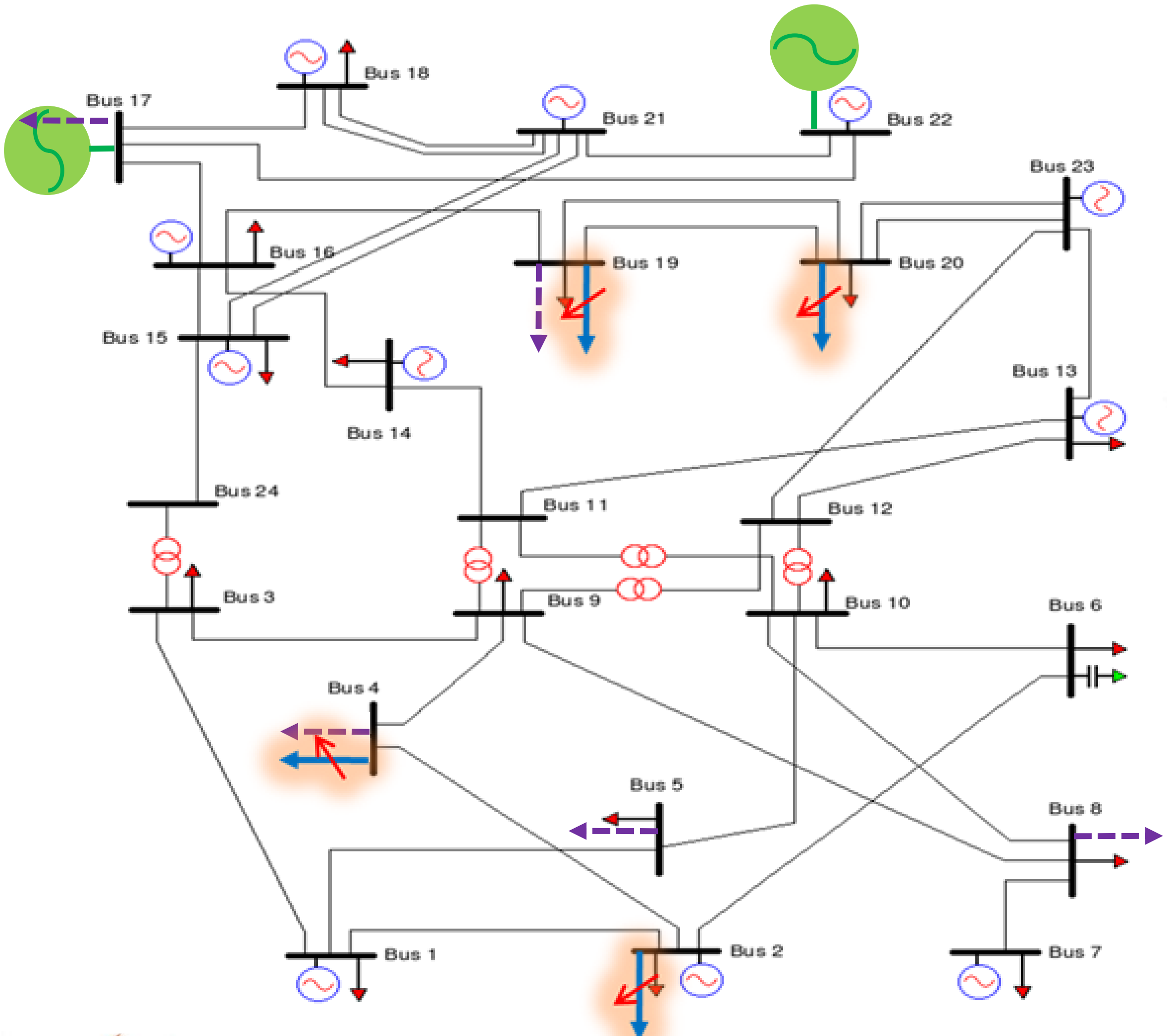




- ❖ Elastic demand that responds to time-varying prices

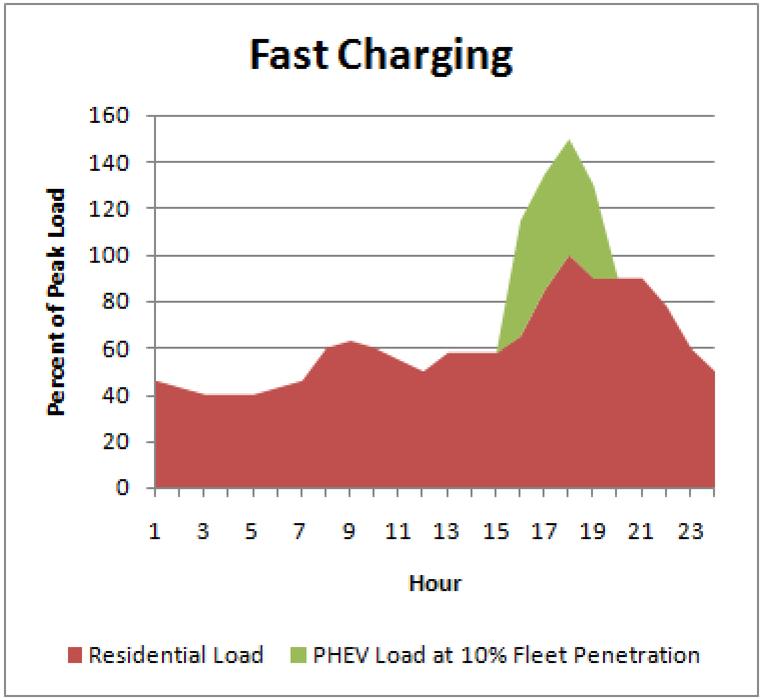

MPC−based DYMONDS Dispatch with 50% Wind
MW
3500
3000
2500
2000
1500
1000
500
0
Load (Inelastic Case)
Total Load (Elastic Case)
Wind generation (Inelastic Load)
Wind Generation (Elastic Load)
0
50
100
150
Time Steps (10 minutes interval)
MW
2000
1500
1000
500
0
Coal output with inelastic load
Coal output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

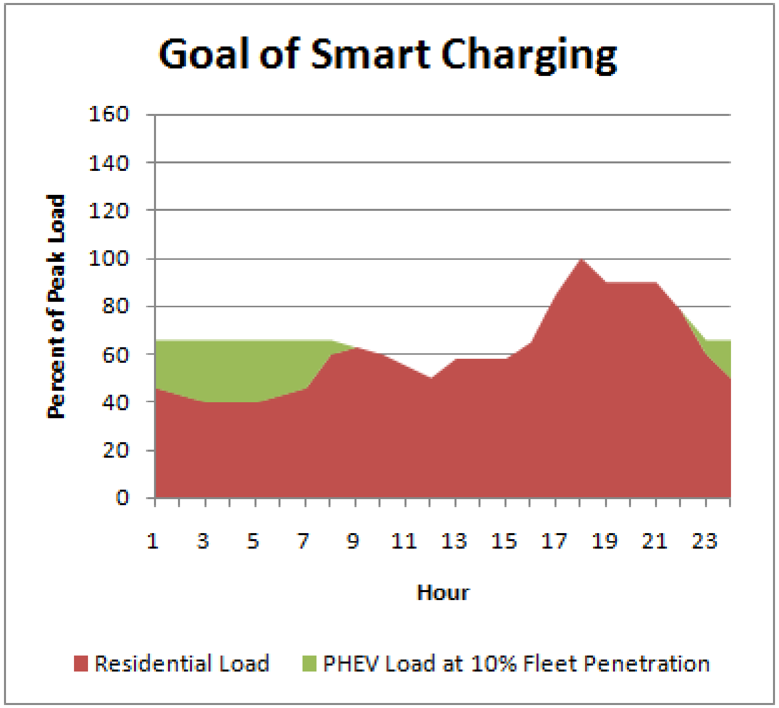
DYMONDS Simulator
Impact of Electric vehicles

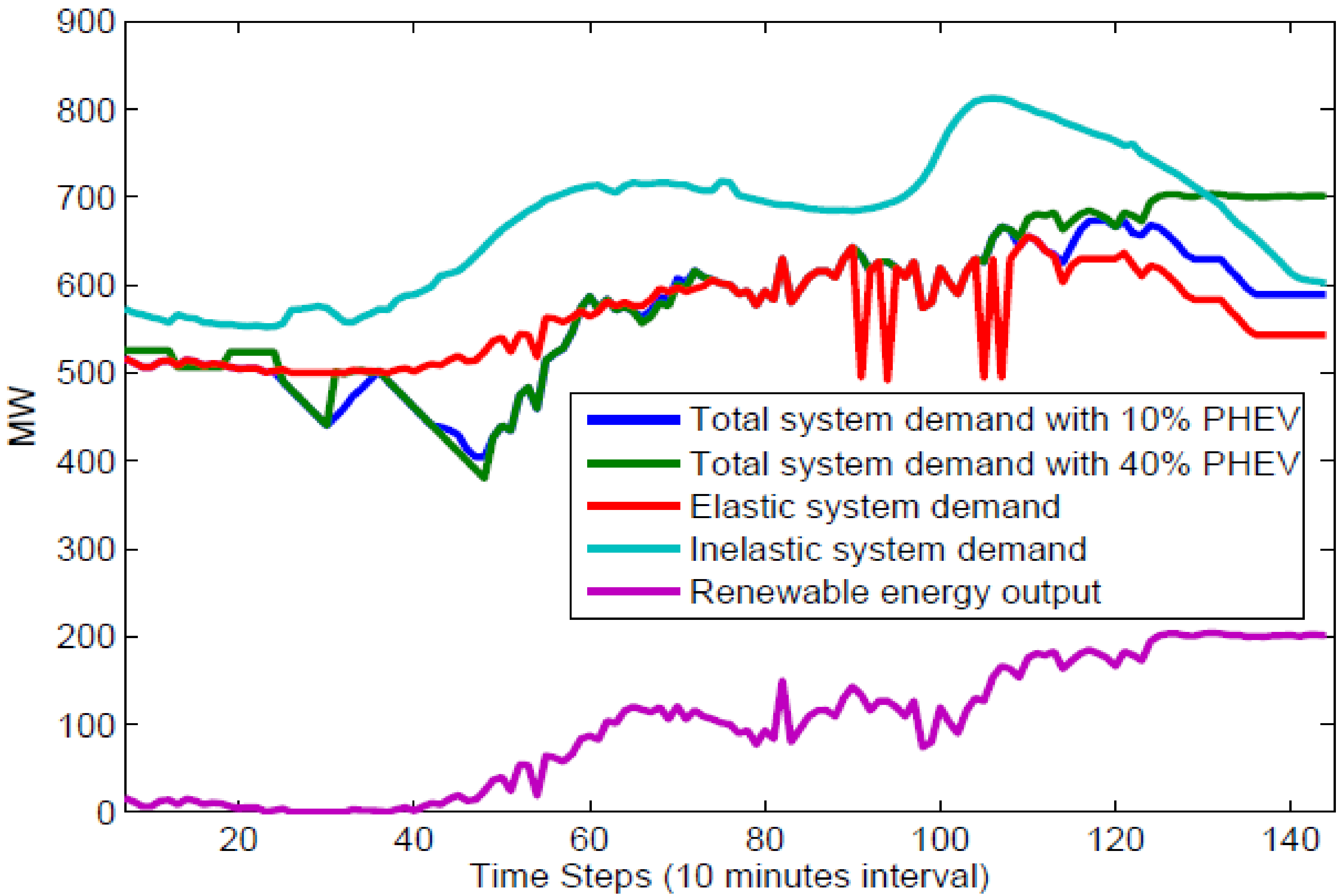


❖ Interchange supply / demand mode by time-varying prices

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



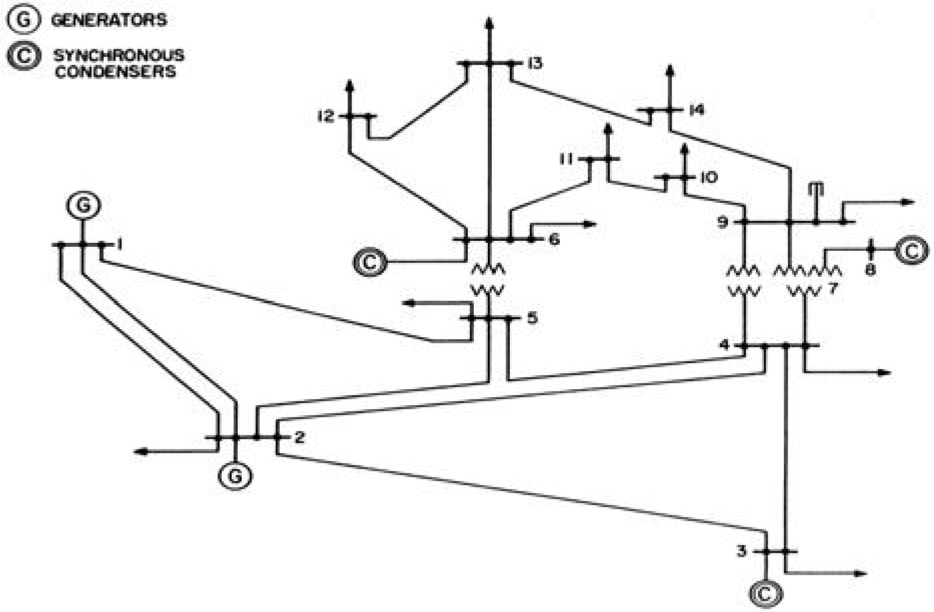



900
800
700
600
500
400
300
200
100
0
MW
20
40
60
80
100
120
140
Time Steps (10 minutes interval)
Total system demand with 10% PHEV
Total system demand with 40% PHEV
Elastic system demand
Inelastic system demand
Renewable energy output

AC OPF +DYMONDS – Proof of concept on 14 bus system

$$P_g^{min} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \quad P_g^{max} = \begin{bmatrix} 450 \\ 60 \\ 143 \\ 160 \\ 100 \end{bmatrix}$$

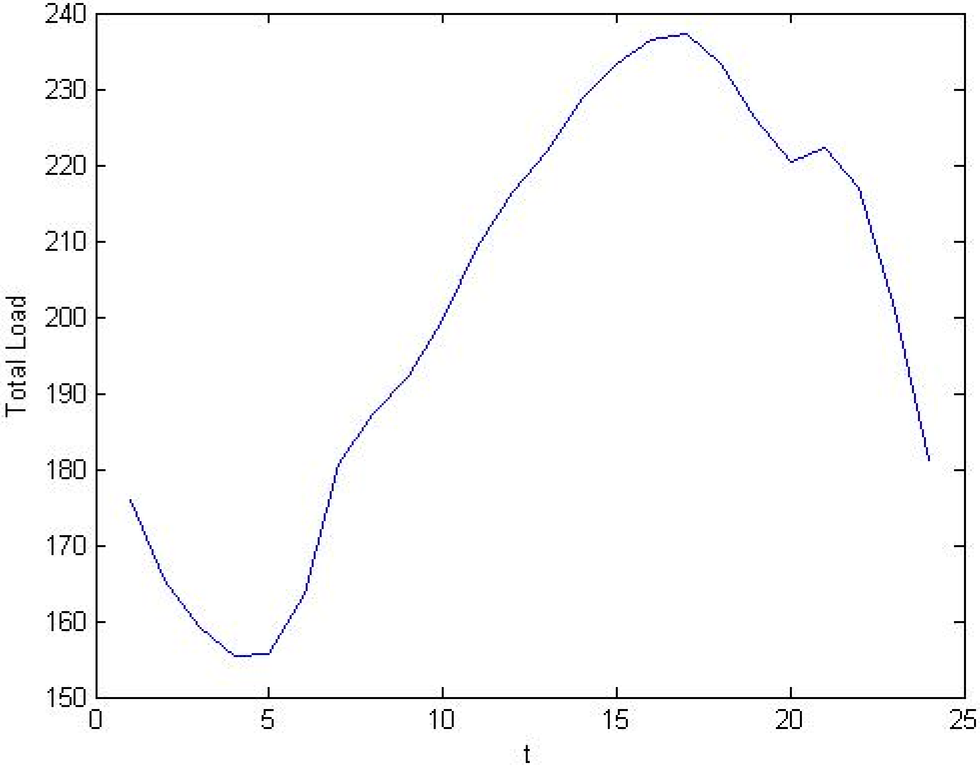
$$Q_g^{min} = \begin{bmatrix} 0 \\ -40 \\ 0 \\ -6 \\ -6 \end{bmatrix} \quad Q_g^{max} = \begin{bmatrix} 10 \\ 50 \\ 40 \\ 24 \\ 24 \end{bmatrix}$$



- Gen. cost (quad,linear):
  - G1: (0.187,7)
  - G2: (0.133, 11.67)
  - G3: (0.116, 9.167)
  - G6: (100, -57.21)
  - G8: (1.75, 7.5)

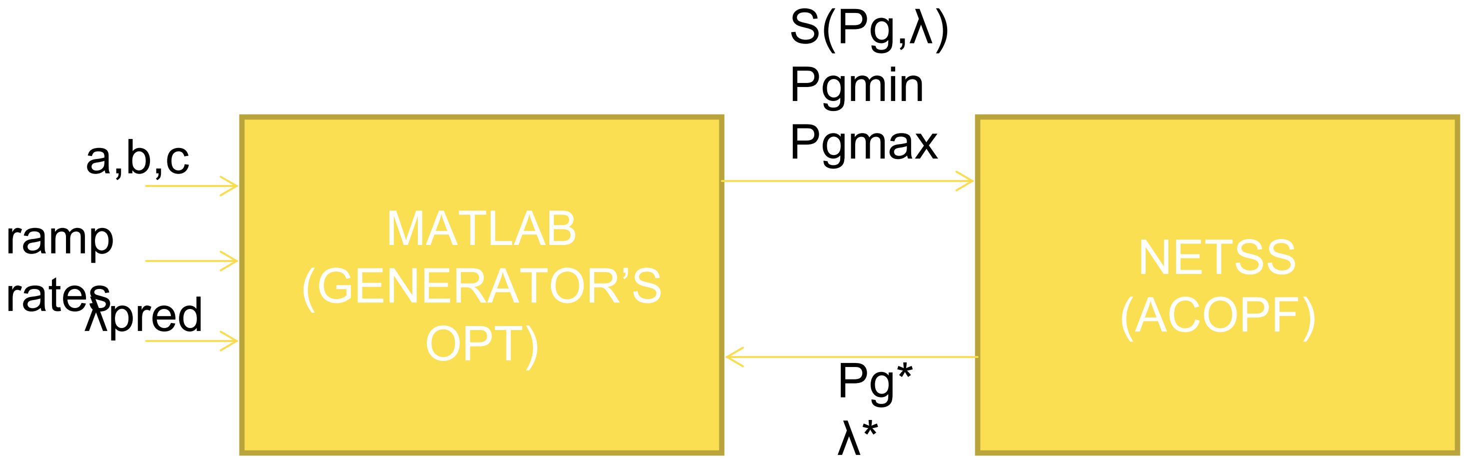
- No line flow limits
- *Vmin=0.94, Vmax=1.06* at all buses
- Predicted price: *\$20/MWh* in 24 hours
- Ramp rates of generators: *50MW/per hour*

Load curve

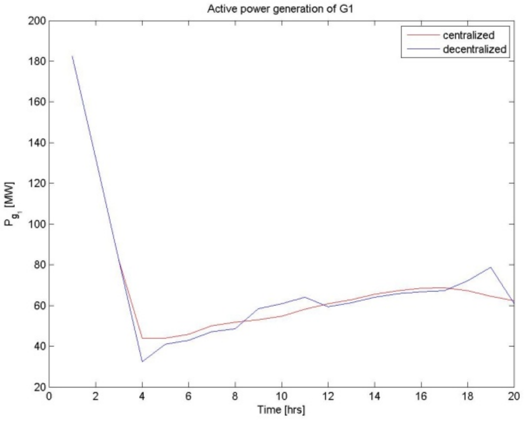


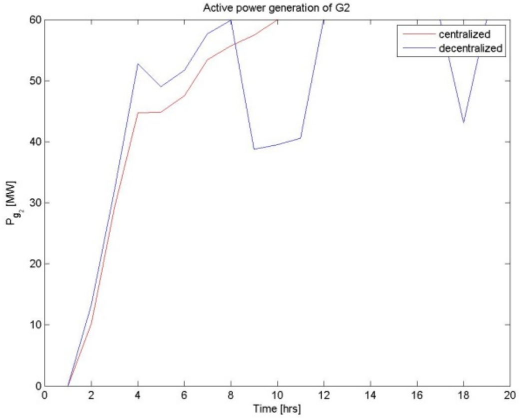
Total Load
t
240
230
220
210
200
190
180
170
160
150
0
5
10
15
20
25

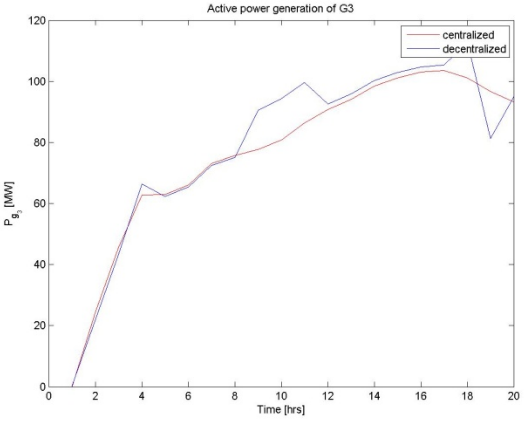
DYMONDS Communication

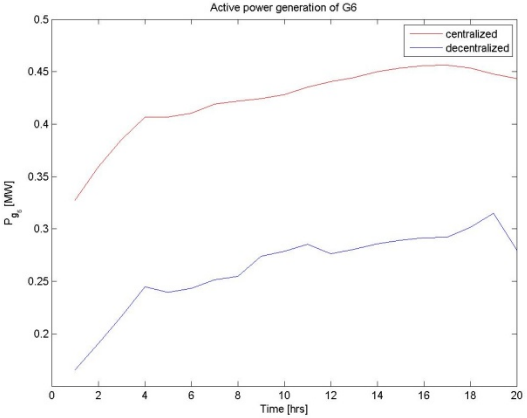


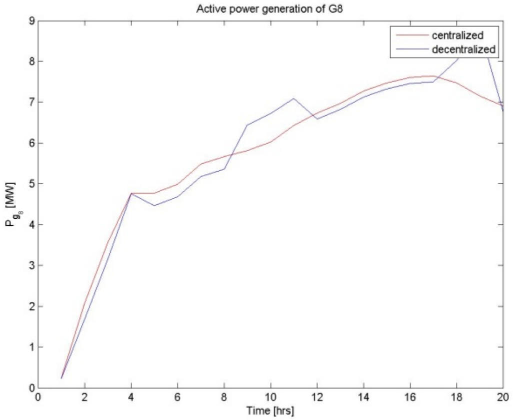
Active Power Generation: Centralized vs. DYMONDS











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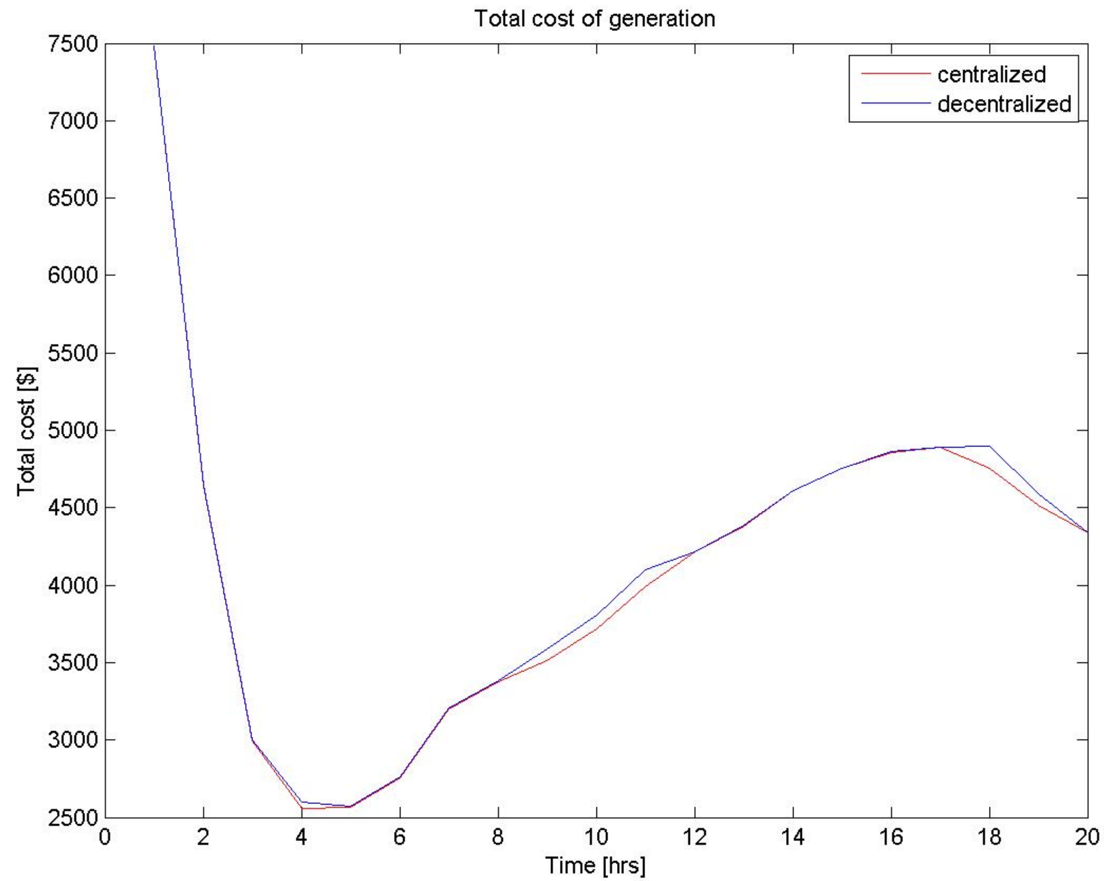
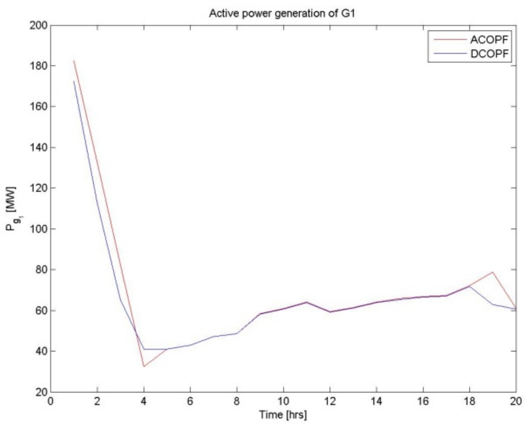
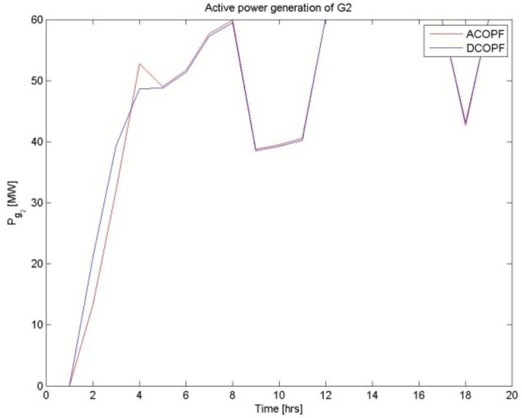
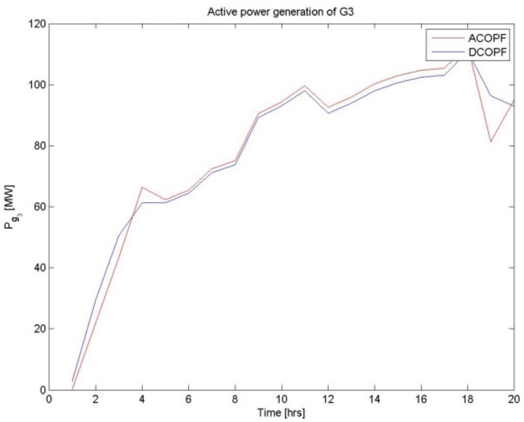
Total Cost: Centralized vs. DYMONDS

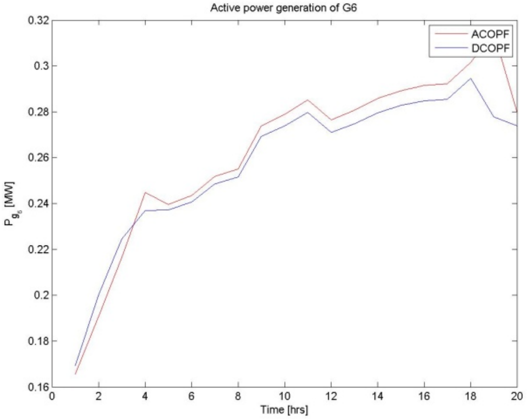


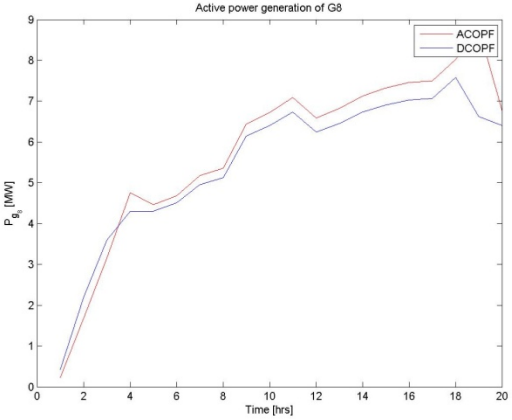
Active Power Generation: DYMONDS (ACOPF vs. DCOPF)



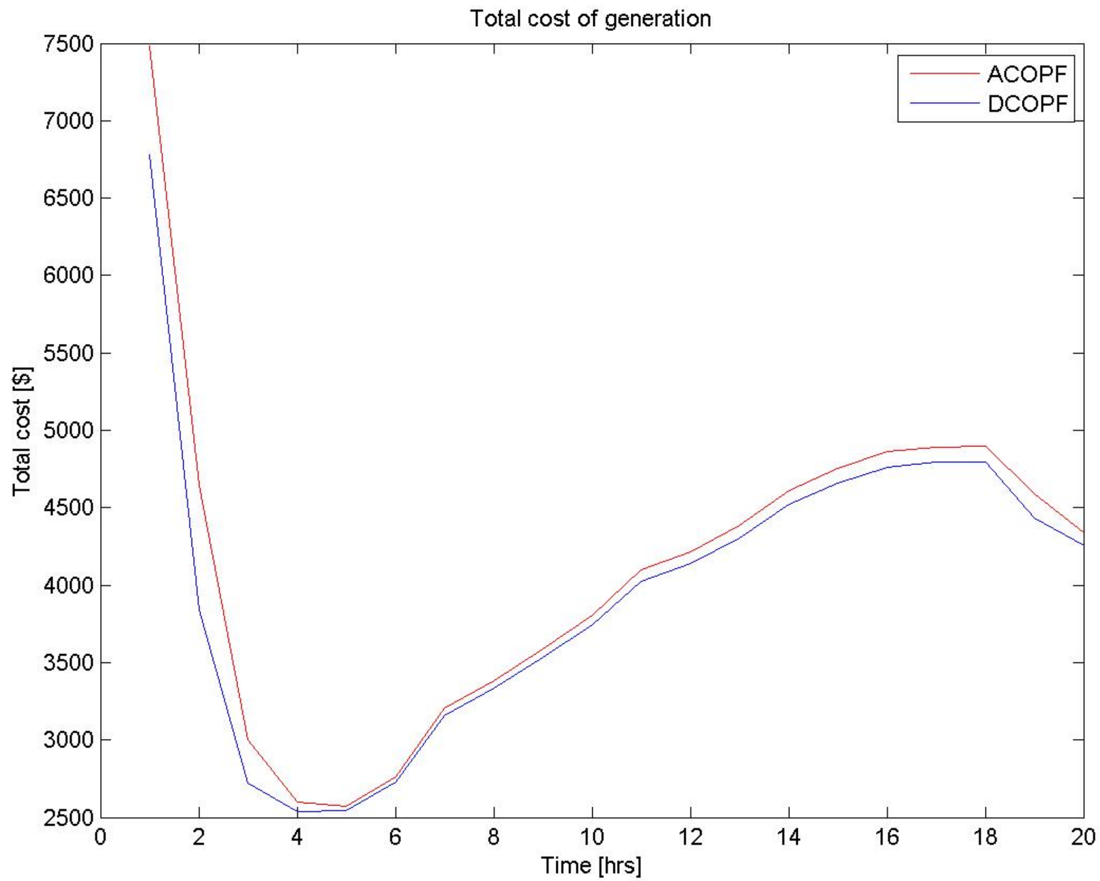








Total Cost: DYMONDS (ACOPF vs. DCOPF)



Concluding remarks: Rethinking limits to complexity

- Impossible to characterize top-down all diverse technologies
- Clear that today' MPC algorithms not scalable as of now;
- Typical approximation—LR w.r.t. time; assumes hierarchical time scale separation of SCED and UC
- LR w.rt. to time questionable with persistent changes in system inputs; complexity will grow with new technologies (physics vs. binary decisions)
- Need to carefully combine nonlinear characteristics of the grid with the uncertain temporal complexities of system users

The challenge of implementing AC OPF

- Many off-line simulations performed in the last few years; potential for reliability and efficiency enhancements
- Close collaboration on analyzing potential benefits has led in three control centers to report their assessment of possible benefits [3]
- Many open questions concerning responsibilities for voltage support in the changing industry
- Need regulatory incentives to reconcile reliability and efficiency objectives and support coordinated voltage control at value to the right parties (DSOs, TSOs, ISOs, producers, LSEs)

References

[1] M. Ilić, L. Xie and J.-Y. Joo, Efficient Coordination of Wind Power and Price-Responsive Demand Part I: Theoretical Foundations, Part II: Case Studies, *IEEE Transactions on Power Systems, 2012.*

[2] Ilic, Marija D., Jeffrey H. Lang, and Eric H. Allen. "The Role of Numerical Tools in Maintaining Reliability During Economic Transfers: An Illustration Using the NPCC Equivalent System Model." Bulk Power System Dynamics and Control VII, August 19-24, 2007, Charleston, SC.

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