# Distributed Look-ahead Coordination of Intermittent Resources and Storage in Electric Energy Systems

Le Xie (Lxie@ece.tamu.edu)

Assistant Professor

Department of Electrical and Computer Engineering

Texas A&M University

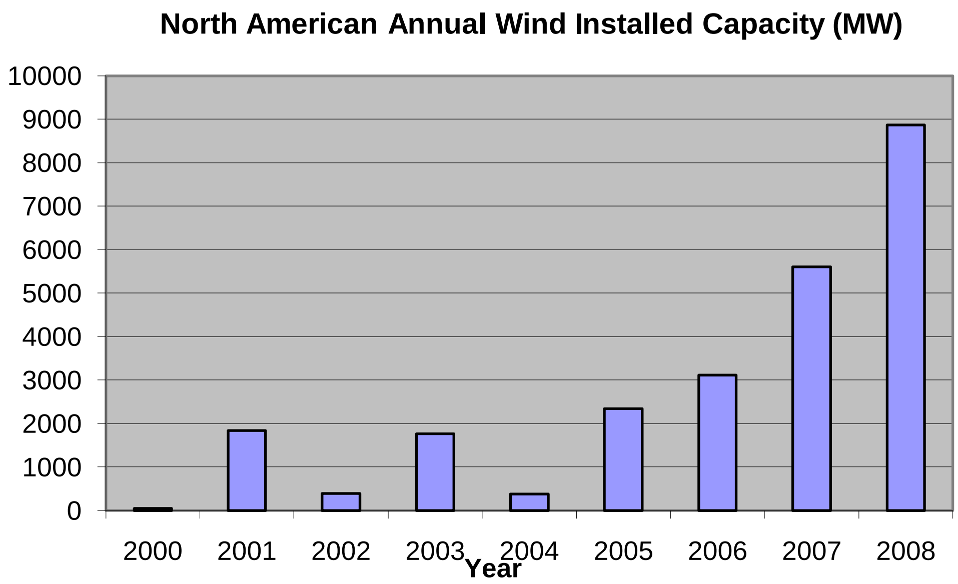
*Talk at Los Alamos National Laboratory*
*May 10, 2011*

Joint work with *Prof. M. Ilic, Prof. J.M.F. Moura, Prof. U. Khan, J. Joo, Y. Gu, A. Thatte*

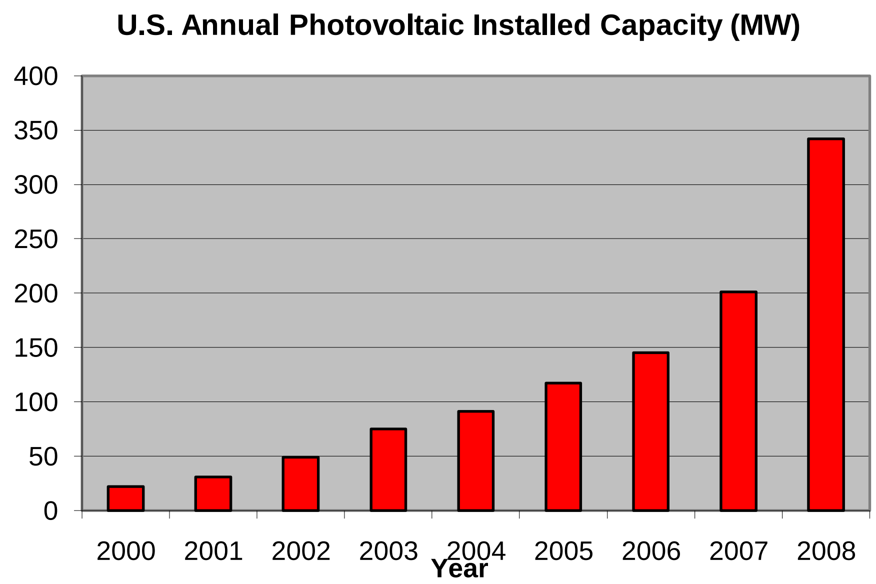
# Outline

- Introduction
- Literature Review
- Proposed Approach and Results
  - Scheduling
  - Dynamic Stability Assessment
- Summary

# Fast-Growing Intermittent Renewable Energy Resources




Source: Global Wind Energy Council




Source: Interstate Renewable Energy Council

TEXAS A&M UNIVERSITY
ELECTRICAL & COMPUTER ENGINEERING

# Smart Grid = IT + Power Grid?


Source: http://www.nazeleno.cz/Files/FckGallery/Smart_Grid2.zip/Smart_Grid2.jpg

# Loss of wind causes Texas power grid emergency

Wed Feb 27, 2008 8:11pm EST

Email | Print | Share | Reprints | Single Page | Recommend (25) [-] Text [+]

HOUSTON (Reuters) - A drop in wind generation late on Tuesday, coupled with colder weather, triggered an electric emergency that caused the Texas grid operator to cut service to some large customers, the grid agency said on Wednesday.

Electric Reliability Council of Texas (ERCOT) said a decline in wind energy production in west Texas occurred at the same time evening electric demand was building as colder temperatures moved into the state.

The grid operator went directly to the second stage of an emergency plan at

**RELATED NEWS**

- Low prices may hamper Texas wind projects
  6:42am EST
- Low prices may hamper Texas wind projects
  10 Apr 2008
- Wind power experts say Texas grid needs work
  10 Apr 2008
- Global wind power capacity rises 27 percent in 2007
  10 Apr 2008
- Texas sees higher costs to reap wind power
  03 Apr 2008

powered by Sphere

News from:
http://www.reuters.com/article/domesticNews/idUSN2749522920080228?feedType=RSS&feedName=domesticNews&rpc=22&sp=true

# The Challenge of Wind Variability

ERCOT's Doggett: Ramping of wind resources 'keeps me awake at night'

By Kelly Harrington
SNL Interactive
10/04/10

Ask Electric Reliability Council of Texas Inc. President and CEO H.B. "Trip" Doggett to name an area of concern, and he will say it is variable wind resources.

"That is one thing that keeps me awake at night," he said in a keynote address Sept. 29 at the Gulf Coast Power Association's fall conference in Austin, Texas. "Steep ramps from wind resources is one thing that concerns both Dan [Woodfin, ERCOT's director of system planning] and I. I think we have to keep our eye on that."

# Cost of High Intermittency

## Wind Power = Dirty Energy?!

Published by Evan Webb, April 17th, 2008 global wa

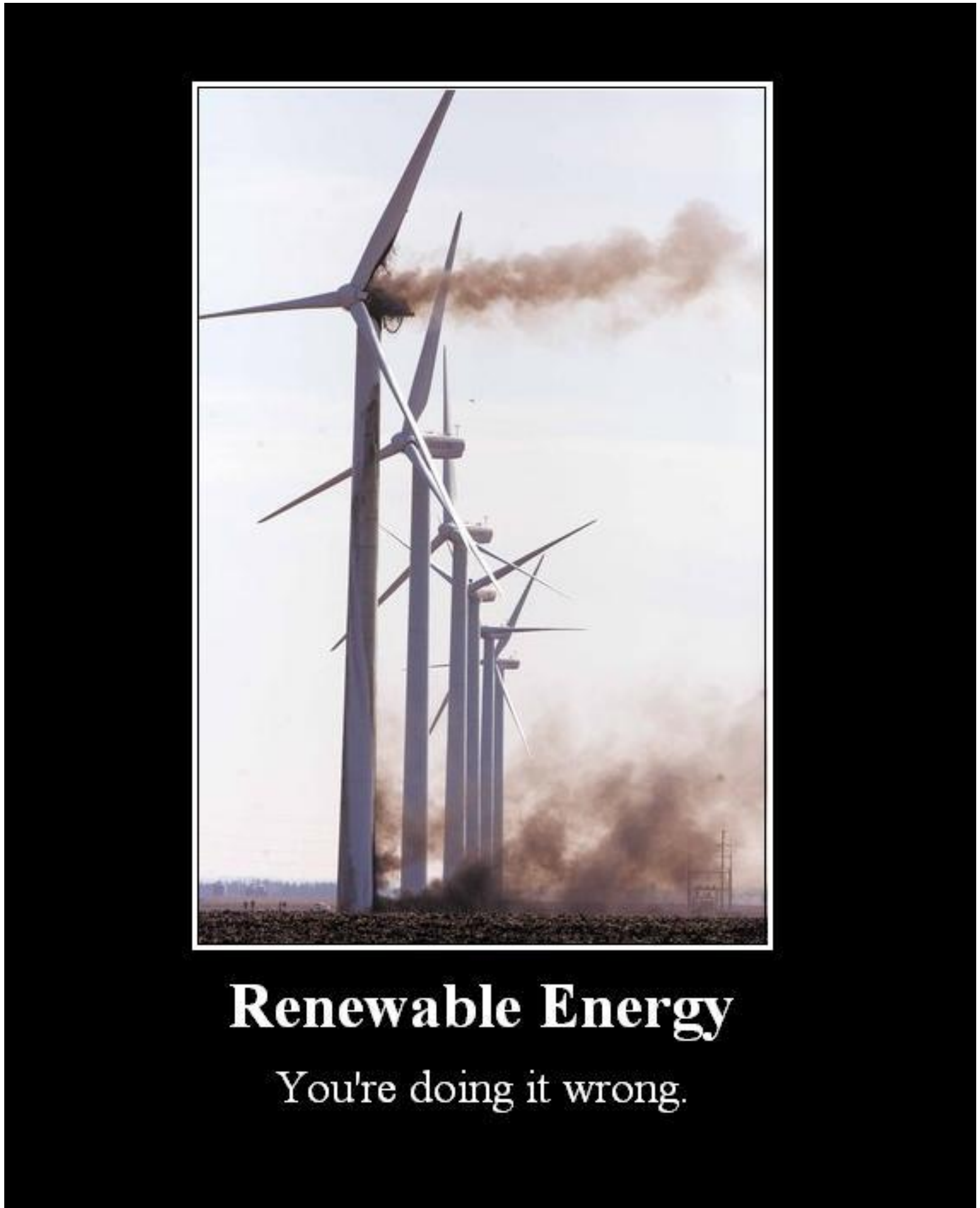
### Backup

Additional backup as a percentage of installed wind capacity

| | |
|---|---|
| 100% | Adam Smith Institute |
| 100% | Prof Michael Laughton |
| 100% | Country Guardian |
| 73-86% | Royal Academy of Engineering |
| 65% | PB Power / RAEng |

Graham Sinden, "Assessing the Costs of Intermittent Power Generation," *University of Oxford Stakeholder Workshop*, 2005.

Image source: http://itsgettinghotinhere.org/2008/04/17/wind-power-dirty-energy/






Source: www.wind-watch.org

# Problem Statement

- Power engineering's perspective:
  - Design efficient scheduling algorithms in support of large-scale *distributed, intermittent* resource integration; both system- and resource-level multiple objectives must be taken into account
- System-theoretic perspective:
  - Pose a centralized resource optimization problem with two qualitatively different types of decision variables

    (1) conventional power generation s.t. time-invariant constraints and specified inter-temporal constraints

    (2) intermittent power generation s.t. time-varying constraints and specified inter-temporal constraints
  - Design a computationally efficient algorithm to solve this optimization problem by enabling interactions of distributed decision making and system coordination.

# Problem Statement

- Power engineering's perspective:
  - Online small-signal stability assessment for the power systems with distributed, non-uniform resources and sensor-based load dynamics
- System-theoretic perspective:
  - Introduce module-based dynamical model that supports frequent topological changes and includes non-uniform resource dynamics
  - Derive sufficient conditions at component- and interconnection-levels to ensure system-wide linearized stability

# Outline

- Introduction
- Literature Review
- Proposed Approach and Results
  - Scheduling
  - Stabilization
- Summary

# Literature Review: System Theory

- Decentralized Control [1, Siljak] [2, Sandell]
  - Weak interconnections among subsystems
  - Fully decentralized (no communication needed)
  - Conservative bounds for stability
- Consensus-based Cooperative Control [3, Olfati-Saber]
  - Applicable to systems with strong interconnections
  - Iterative communication among subsystems to reach consensus of system states
  - Potentially high communication cost for large-scale systems with non-uniform components

[1] D.D. Siljak, *Large-scale Dynamic Systems, New York: North-Holland, 1978.*

[2] N.R. Sandell, P. Varaiya, M. Athans, and M.G. Safonov, “Survey of decentralized control methods for large scale systems,” *IEEE Transactions on Automatic Control,* Vol. AC-23, Issue 2, pp. 108-128, Apr 1978.

[3] R. Olfati-Saber, J. A. Fax, and R. M. Murray, “Consensus and cooperation in networked multi-agent systems,” *Proceedings of the IEEE,* Vol. 95, Issue 1, pp.215-233, Jan 2007.

# Literature Review: Power Engineering

- Component Level [4, Muljadi], [5, Hering]
  - Advanced control of intermittent generation dynamics
  - Improved prediction of intermittent resources' output
- System Level [6, Gautam], [7, Wu]
  - Simulation-based system-wide studies
  - Needs for designing novel power systems' models to incorporate available information from distributed resources

[4] E. Muljadi and C.P. Butterfield, "Pitch-controlled variable-speed wind turbine generation," *IEEE Transactions on Industry Applications*, Vol. 37, Issue 1, pp.240-246, Jan 2001.
[5] A. Hering and M. G. Genton, "Powering Up With Space-Time Wind Forecasting," *Journal of the American Statistical Association,* Vol. 105, No. 489, pp. 92-104, March 2010.
[6] D. Gautam, V. Vittal, T. Harbour , "Impact of Increased Penetration of DFIG-Based Wind Turbine Generators on Transient and Small Signal Stability of Power Systems," *IEEE Transactions on Power Systems,* Vol. 24, No. 3, pp. 1426-1434, Aug. 2009
[7] F. F. Wu, K. Moslehi, and A. Bose, "Power system control centers: past, present, and future," *Proceedings of the IEEE,* Vol. 93, Issue 11, pp.1890-1908, Nov 2005.

# What's Needed

Component Level

System Level

?

Better prediction and control of variable resources

Advanced IT (sensors, actuators and communication devices)

Stable system operation with intermittent resources

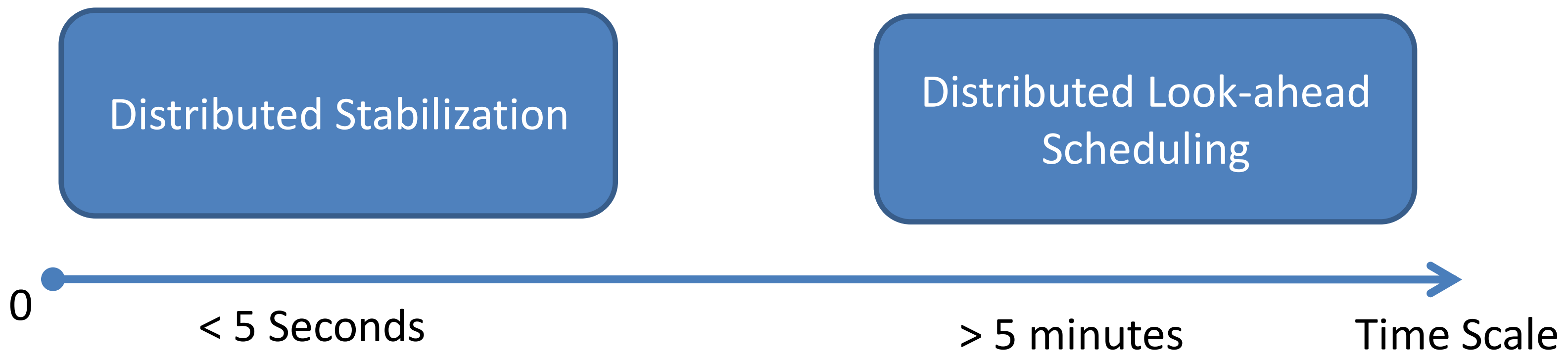
Reduce system cost for meeting diverse objectives with variable resources

# Outline

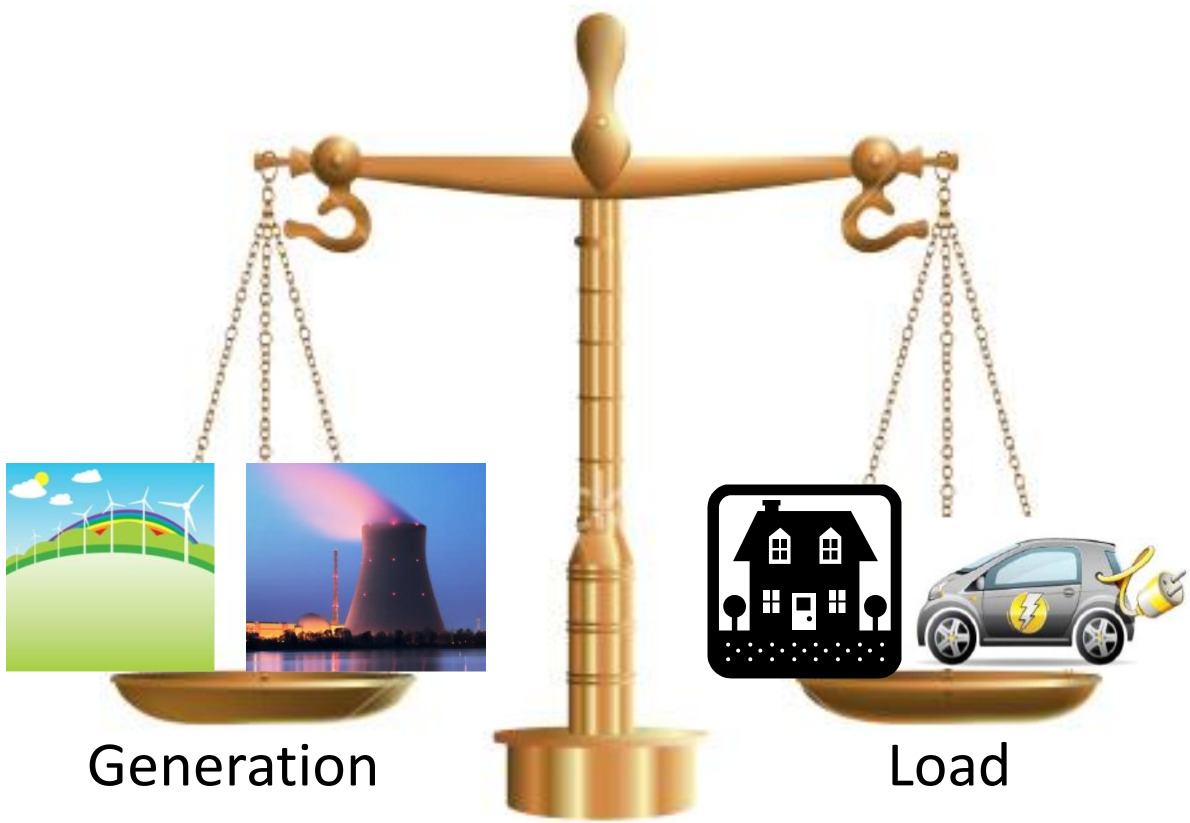
- Introduction
- Literature Review
- Proposed Approach and Results
  – Scheduling
  – Stabilization
- Summary

# What We Propose

- A *system-theoretic* approach to
  - Modeling
  - Stabilizing
  - Scheduling
- Potential of quantifiable performances with *distributed intermittent* resources in electric energy systems.

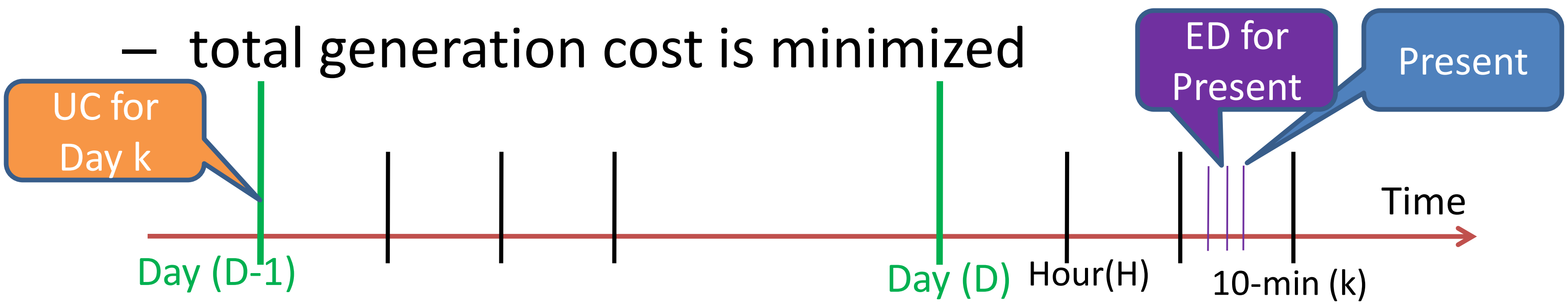


# Part I: Distributed Look-ahead Scheduling for Enhanced Efficiency



# Generation Scheduling: UC and ED [8]

- Unit Commitment (UC): for the forecasted demand, how to turn ON and OFF available units given day or week ahead demand forecast
- Economic Dispatch (ED): given a mixture of energy resources, how to determine the output of individual energy resources so that
  - power supply always balances forecast net demand
  - total generation cost is minimized




[8] M. Ilic, F. Galiana, and L.Fink, *Power Systems Restructuring: Engineering and Economics*, Norwell, MA: Kluwer, 1998

# Net Demand—No Wind

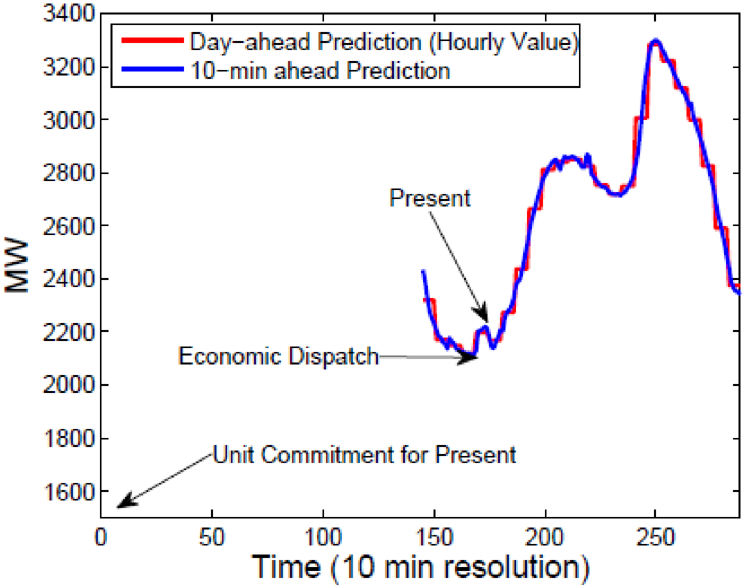



Fig. 2. Day-ahead and 10-min ahead load prediction, and timing of UC and ED functions

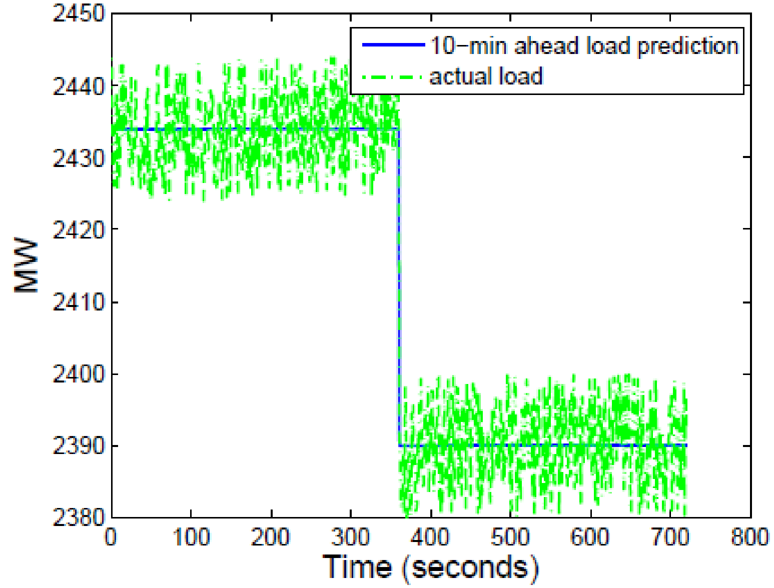



Fig. 3. 10-min ahead load prediction and second-by-second actual load

$$L(t) = \hat{L}[H] + \Delta_{LH}(t)$$ (Day-ahead forecast)

$$L(t) = \hat{L}[k] + \Delta_{Lk}(t)$$ (10-minute ahead forecast)

$$\left\|\hat{L}[H]\right\| \gg \|\Delta_{LH}(t)\|$$

$$\|\Delta_{LH}(t)\| > \|\Delta_{Lk}(t)\|.$$

(Day-ahead forecast *reasonably good*)


[9] L. Xie, P. M. S. Carvalho, L. A. F. M. Ferreira, J. Liu, B. Krogh, N. Popli, and M. D. Ilić, "Integration of Variable Wind Energy in Power Systems: Operational Challenges and Possible Solutions," *Proceedings of The IEEE: Special Issue on Network Systems Engineering for Meeting the Energy and Environment Dream* (2011)

# With High Wind Penetration

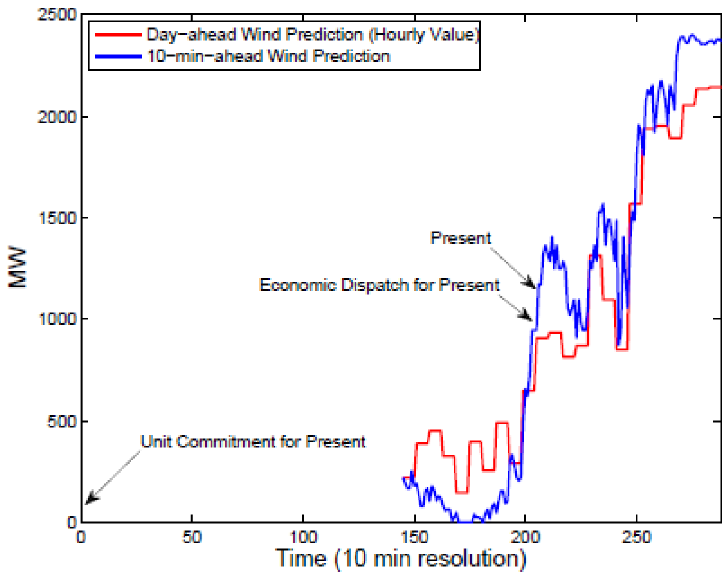



Fig. 4. Day-ahead and 10-min ahead wind prediction, timing of UC and ED functions

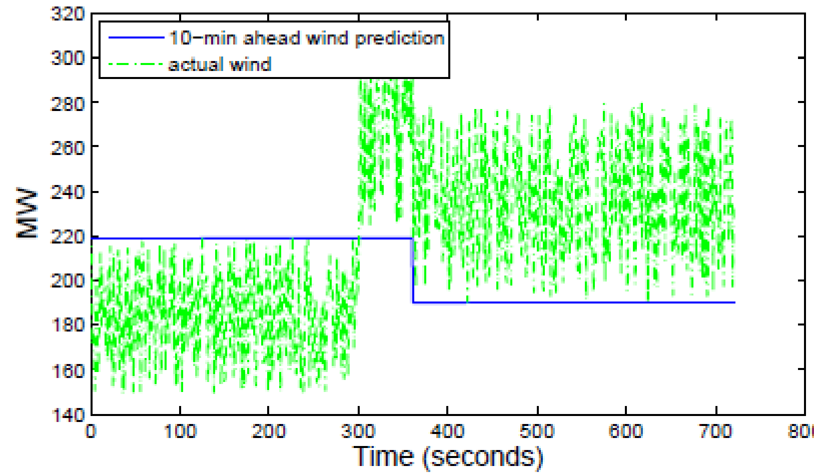



Fig. 5. 10-min ahead wind prediction and second-by-second actual wind

$$P_{Gw}(t) = \hat{P}_{Gw}[H] + \Delta_{Gw_H}(t)$$ (Day-ahead forecast)

$$P_{Gw}(t) = \hat{P}_{Gw}[k] + \Delta_{Gw_k}(t)$$ (10-minute ahead forecast)

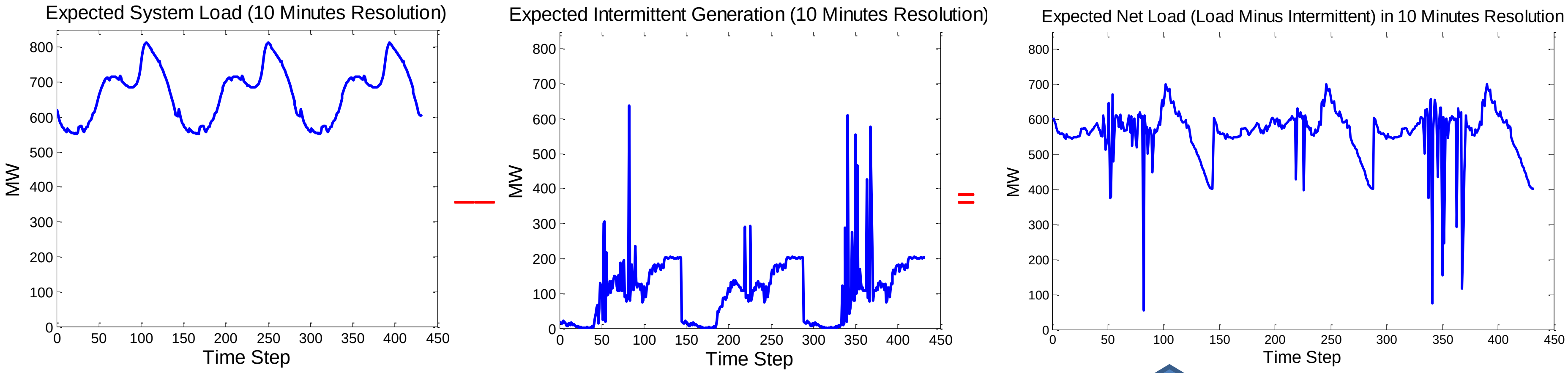
$$\|\Delta_{Gw_H}(t)| \gg \|\Delta_{Gw_k}(t)\|$$

$$\|\hat{P}_{Gw}[k]\| \gg \|\Delta_{Gw_k}(t)\|.$$

(*Substantial accuracy improvement* from Day-ahead to 10-min-ahead)

# Conventional Approach to ED

- Supply the expected load with whatever produced by intermittent resources combined with other traditional power plants




Economic Dispatch (ED): Choose output levels from conventional power plants to meet the “net load” at minimum cost.

# Key Problems with Conventional ED

- Significant need for fast and expensive units (e.g. natural gas)
- Under utilization of slow responding units
- Pollution caused by volatile ramping of fast units
- Consequently, higher O&M cost and avoidable pollution
- No incentives to reduce ramping rate-related costs (socialized UC cost)

# Benchmark for Better Dispatch Methods

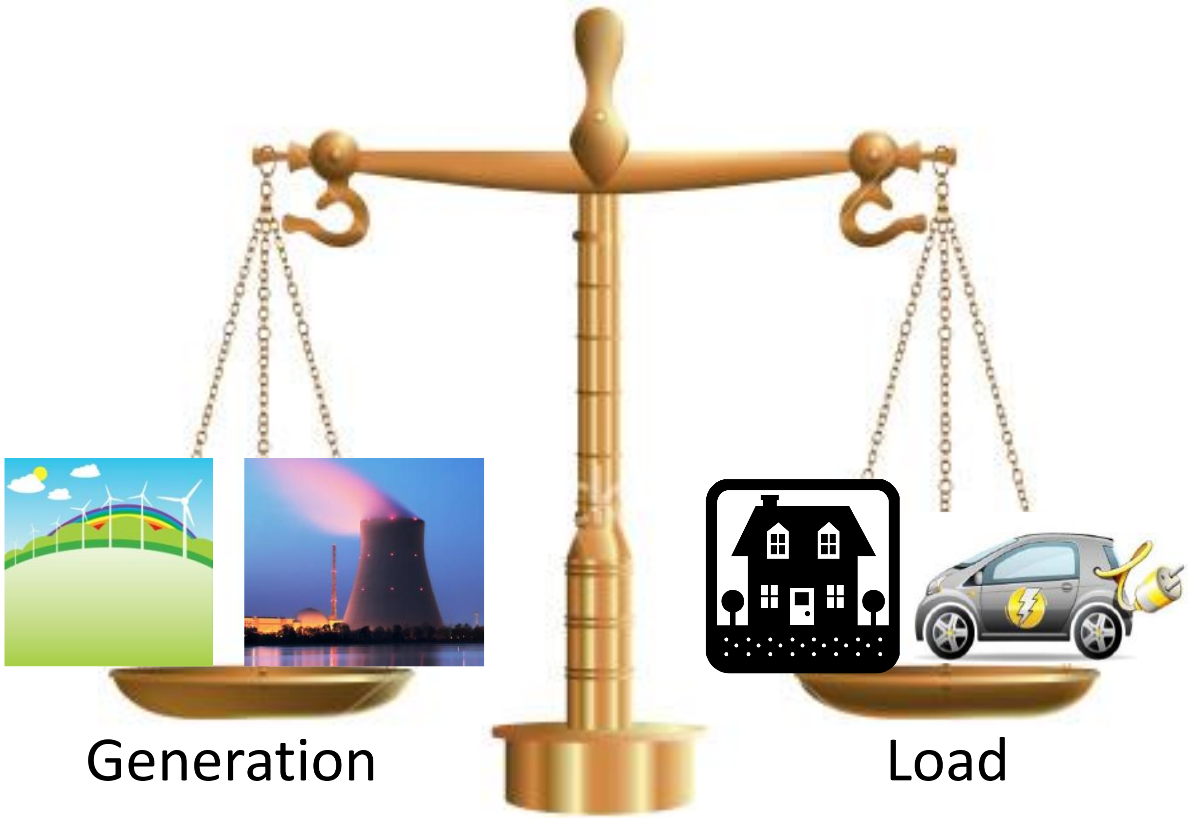
- Capable of optimizing under uncertainties
- Capable of utilizing near-term better forecast
- Computationally manageable
- Provide ramping-rate related incentives
- Coordinate O&M and emission costs at value

# Related Work

- Wind forecasting techniques constantly improving [Botterud, Wang, Miranda, Bessa 2010]
- Improved economic benefits due to dynamic look-ahead dispatch [Ross, Kim, 80] [Xie, Ilic, 09]
- Coordinating deferrable demands with variable generation [Papavasiliou, Oren, 2010]
- Impact of real-time pricing on usage of wind generation [Sioshansi, Short, 2008]
- Industry transition from static dispatch to look-ahead dispatch [Ott, 2010]

# Our Proposed Framework: Distributed Look-ahead Dispatch [10]

Model Predictive Control (MPC)



Generation

Load

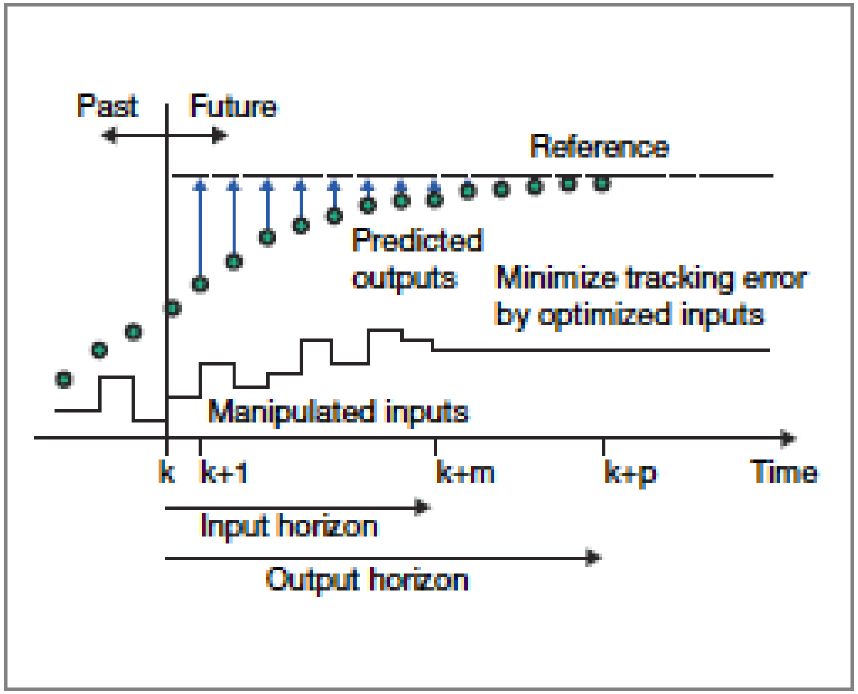
[10] M. Ilic, L. Xie, and J. Joo, "Efficient Coordination of Wind Power and Price-Responsive Demand Part I: Theoretical Foundations", IEEE Transactions on Power Systems (Accepted)

# Our Proposed Framework: Distributed Look-ahead Dispatch [10]

- Takes into account the inter-temporal constraints of different generation technology (*ramping rates*), including wind and storage
- Determine the portions (or aggregated portions) of available intermittent generation outputs into the grid
- Reduce the need for expensive fast-start fossil fuel units
- One possible technique to implement this approach is *model predictive control*

[10] Marija Ilic, Le Xie, and Jhi-Young Joo, "Efficient Coordination of Wind Power and Price-Responsive Demand Part I: Theoretical Foundations", IEEE Transactions on Power Systems (accepted)

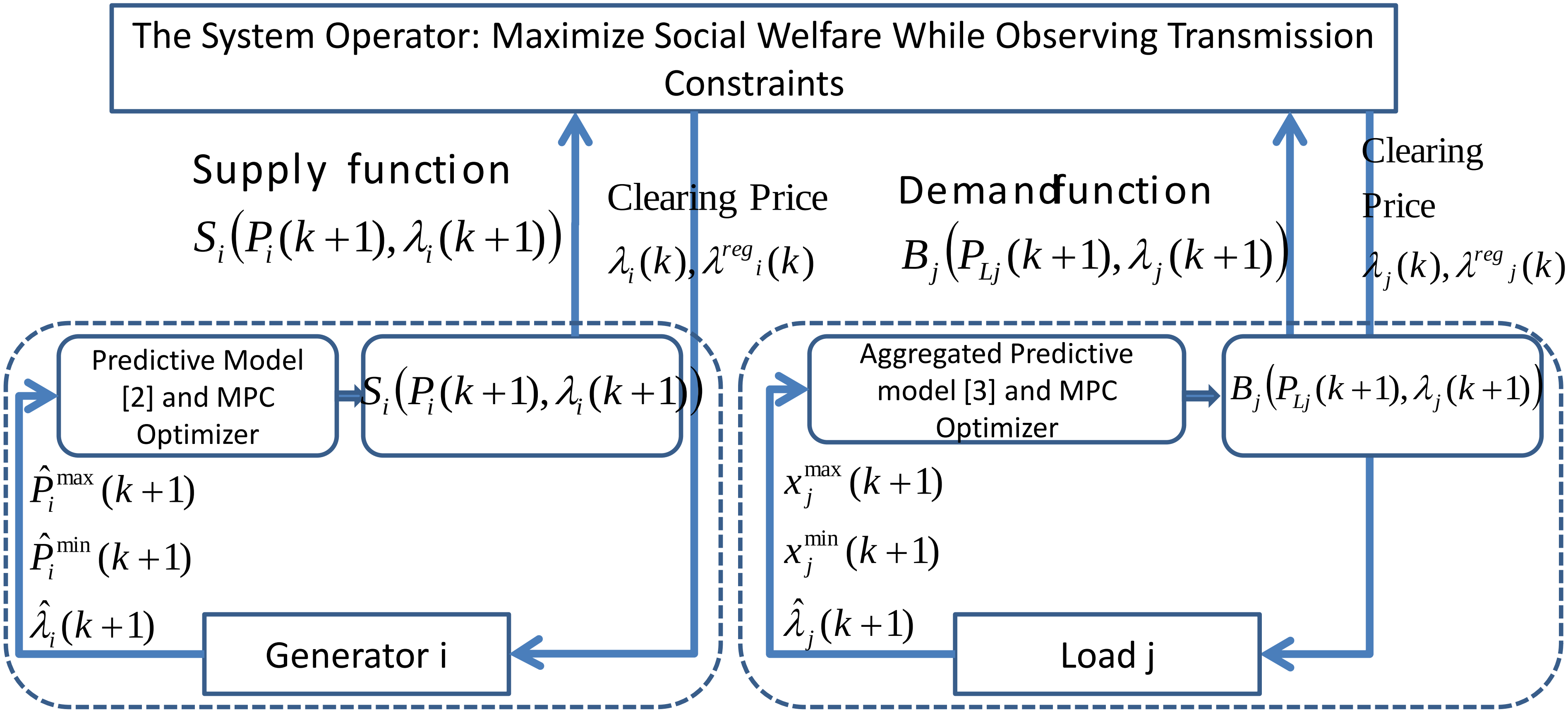
# Model Predictive Control: Concept




www.jfe-rd.co.jp/en/seigyo/img/figure04.gif

- MPC is receding-horizon optimization based control.
- At each step, a finite-horizon optimal control problem is solved but only one step is implemented.
- MPC has many successful real-world applications.

# Implementation under Competitive Market




[10] Marija Ilic, Le Xie, and Jhi-Young Joo, “Efficient Coordination of Wind Power and Price-Responsive Demand Part II: Case Studies”, IEEE Transactions on Power Systems (accepted)
[5] A. Hering and M. G. Genton, “Powering Up With Space-Time Wind Forecasting,” *Journal of the American Statistical Association,* Vol. 105, No. 489, pp. 92-104, March 2010.

# Problem Formulation: At Wind Generator Level

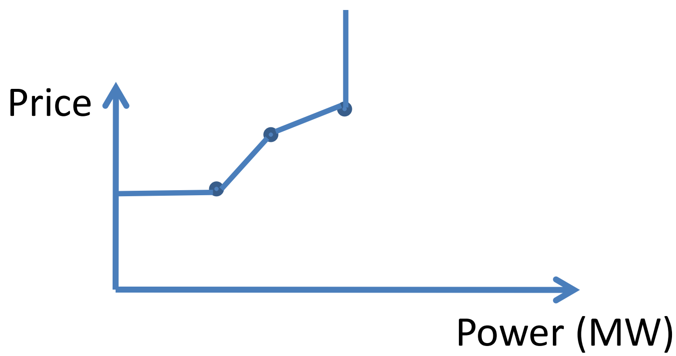
$$
\begin{aligned}
\text{Solve}: \max_{P_{G_i}} \sum_{k=1}^{K} & E[\hat{\lambda}(k)(P_{G_i}(k)) - C_i(P_{G_i}(k)) \\
& - \hat{C}_p(k)(\Delta G_i(k) - r * P_{G_i}(k))^{+}] \\
\text{s.t. } & \hat{P}_{G_i}^{max}(k) = g_i(P_{G_i}^{max}(k-1), \cdots, P_{G_i}^{max}(k-N)); \\
& |P_{G_i}(k+1) - P_{G_i}(k)| \leq R_i; \\
& P_{G_i}^{\min} \leq P_{G_i}(k) \leq \hat{P}_{G_i}^{\max}
\end{aligned}
$$

Max (Expected Profit)

Wind Forecast

Ramp Rate Constraints

Gen Capacity Constraint




r = 10% in ERCOT nodal market, *ERCOT nodal protocols*, July 2010

# At Elastic Demand Level (e.g. Building Load Serving Entities)

$$\min_{P_i(k)} \sum_{k=1}^{24} [P_i(k) \cdot \hat{\lambda}(k) + \{(x_i(k) - x_i^{\max})^2 + (x_i(k) - x_i^{\min})^2\}] \tag{41}$$

Min (Cost)

$$\text{s.t.} \quad x_i(k+1) = \varepsilon x_i(k) + (1-\varepsilon)(T_o(k) - \gamma P_i(k)) \tag{42}$$

Thermal dynamics

$$x_i^{\min} \leq x_i(k) \leq x_i^{\max} \text{ for all } k \tag{43}$$

Temperature Bound

[11] Marija Ilic, Le Xie, and Jhi-Young Joo, "Efficient Coordination of Wind Power and Price-Responsive Demand Part II: Case Studies", IEEE Transactions on Power Systems (accepted)

# At Storage Level (e.g. Aggregated PHEVs)

$$
\begin{aligned}
\min J \;=\; & \sum_{k=1}^{T} \left[-\lambda_{el}(k) P_{WG}^{sch}(k) + C_w(P_{WG}^{sch}(k))\right] \\
& + \sum_{k=1}^{T} C_p \Delta P_{WG}^{net}(k) + \sum_{k=1}^{T} \left[-\lambda_{el}(k) P_{VG}(k)\right. \\
& \left. -\lambda_{rup}(k) P_{rup}^{cap}(k) - \lambda_{rdn}(k) P_{rdn}^{cap}(k)\right] \\
& + \sum_{k=1}^{T} C_{bt} \left[P_{VG}(k+1) - P_{VG}(k)\right]^2
\end{aligned}
$$

Max (Expected Profit)

s.t.

$$
\begin{aligned}
E(k) &= E(k-1) - P_{VG}(k) - \eta P_{avg} \\
P_{VG}(k) + P_{rup}^{cap.}(k) + P_{EX}^{cap.}(k) &= P_{\max} \\
P_{VG}(k) - P_{rdn}^{cap.}(k) - P_{EX}^{cap.}(k) &= -P_{\max}
\end{aligned}
$$

Energy charging dynamics

$$
\begin{aligned}
-P_{\max} \le P_{VG}(k) &\le P_{\max} \\
E_{\min} \le E(k) &\le E_{\max}
\end{aligned}
$$

Capacity constraints

[12] L. Xie, Y. Gu, A. Eskandari, and M. Ehsani, "Fast MPC-based Coordination of Wind Power and Battery Energy Storage Systems," *submitted to IEEE Transactions on Industrial Electronics*.

# Coordinating of Wind and Battery Energy Storage System using MPC

$$\begin{aligned}\min J \quad = \quad & \sum_{k=1}^{T} \left[-\lambda_{el}(k) P_{WG}^{sch}(k) + C_w(P_{WG}^{sch}(k))\right] \\ & + \sum_{k=1}^{T} C_p \Delta P_{WG}^{net}(k) + \sum_{k=1}^{T} \left[-\lambda_{el}(k) P_{VG}(k)\right. \\ & \left.-\lambda_{rup}(k) P_{rup}^{cap}(k) - \lambda_{rdn}(k) P_{rdn}^{cap}(k)\right] \\ & + \sum_{k=1}^{T} C_{bt} \left[P_{VG}(k+1) - P_{VG}(k)\right]^2\end{aligned}$$

Max (Expected joint profit from energy and regulation services)

Subject to

$$E(k) = E(k-1) - P_{VG}(k) - \eta P_{avg}$$

Charging/discharging dynamics

$$P_{VG}(k) + P_{rup}^{cap.}(k) + P_{EX}^{cap.}(k) = P_{\max}$$

$$P_{VG}(k) - P_{rdn}^{cap.}(k) - P_{EX}^{cap.}(k) = -P_{\max}$$

$$\Delta P_{WG}^{net}(k) = \left\| P_{WG}^{act}(k) - P_{EX}^{act}(k) - P_{WG}^{sch}(k) \right\|$$

Net power injection error

$$-P_{\max} \leq P_{VG}(k) \leq P_{\max}$$

$$0 \leq E(k) \leq E_{\max}$$

$$0 \leq P_{EX}^{cap} \leq P_{\max}$$

$$0 \leq P_{rup}^{cap} \leq P_{\max}$$

Capacity constraints

$$0 \leq P_{rdn}^{cap} \leq P_{\max}$$

$$P_{EX}^{act} \leq P_{EX}^{cap}$$

$$0 \leq P_{WG}^{sch}(k) \leq \hat{P}_{WG}^{\max}(k)$$

$$-P_{WG}^{ramp} \leq P_{WG}^{sch}(k+1) - P_{WG}^{sch}(k) \leq P_{WG}^{ramp}$$

Ramping constraints

# Problem Formulation: At System Operator Level

$$\text{Solve}: \min_{P_G, L} \sum_{i \in G} (C_i(P_{G_i}(k))) - \sum_{z \in Z} (B_z(L_z(k))),$$

Max (Social Welfare)

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

Power Balance

$$P_{G_i}^{min}(k) \le P_{G_i}(k) \le P_{G_i}^{max}(k), i \in G;$$

$$L_z^{min}(k) \le L_z(k) \le L_z^{max}(k), z \in Z;$$

Capacity Constraints

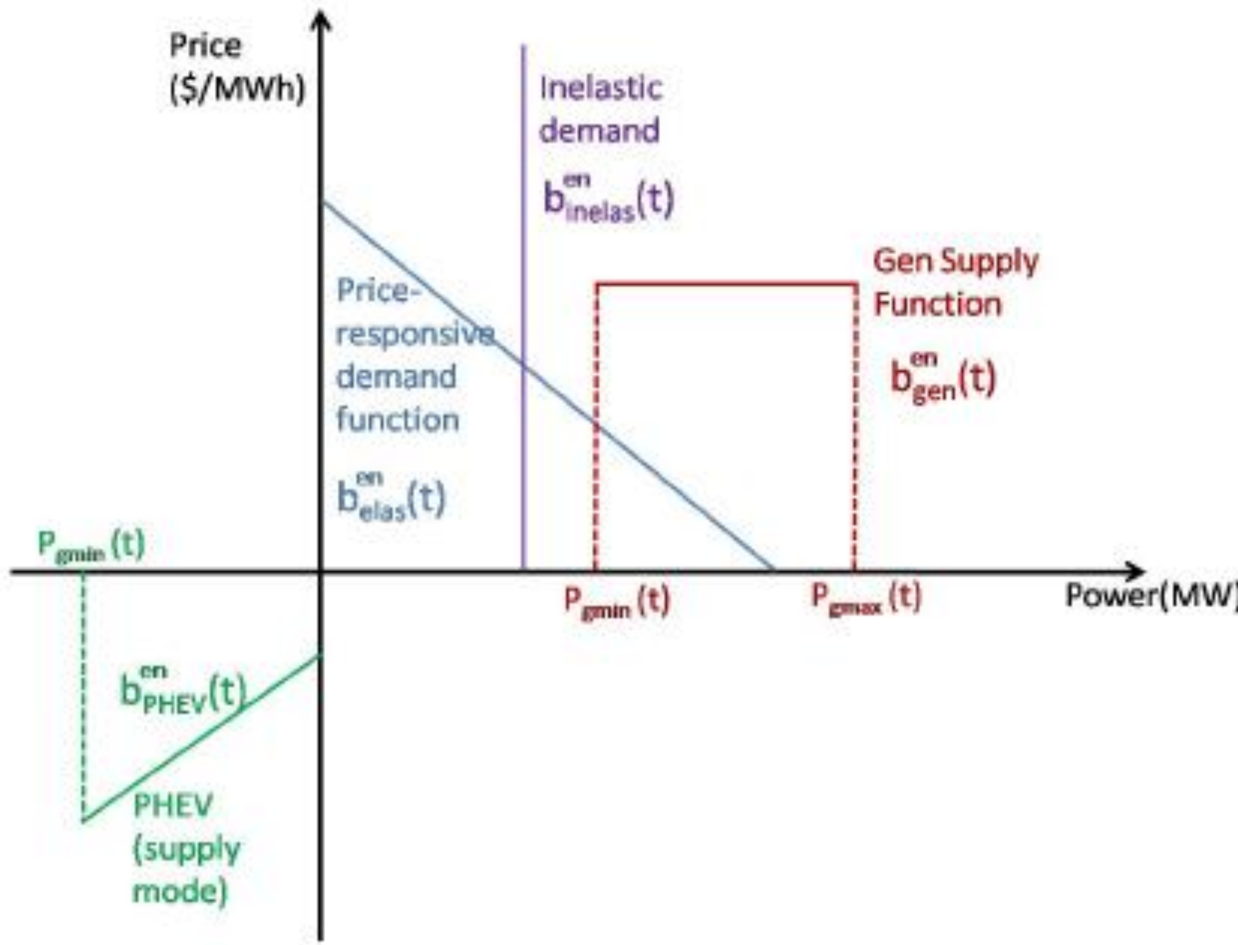
$$|F(k)| \le F^{max};$$

Transmission Constraints

$$AS(k) \ge h(\sum L_z^{max}, \sum P_{Gw_i}^{max})$$

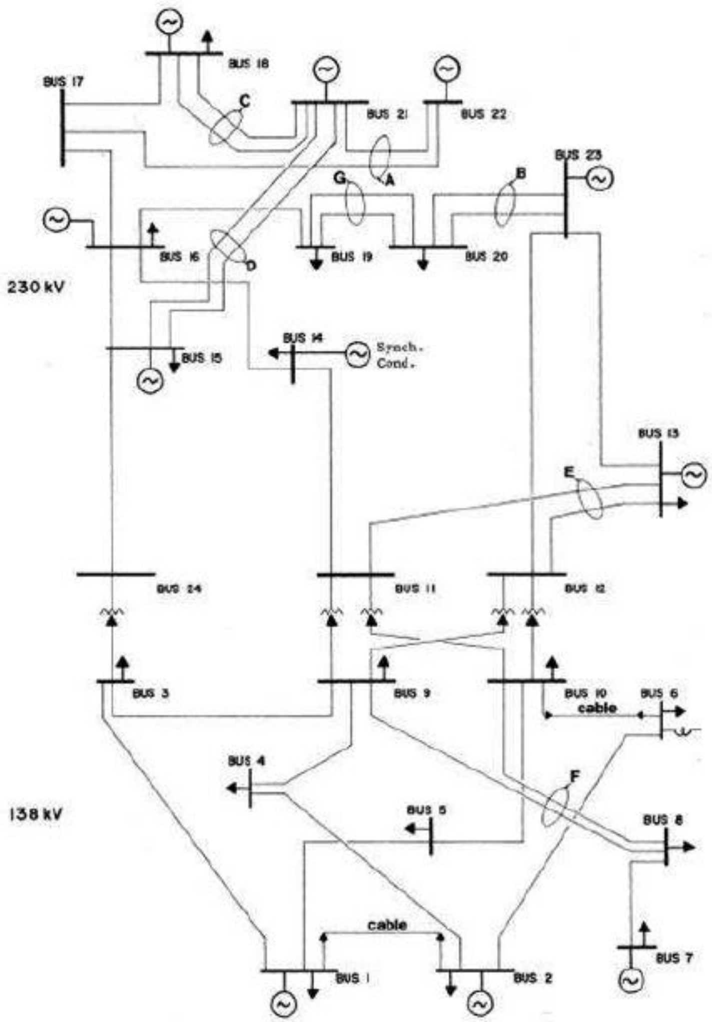
Ancillary Service Requirements

# Typical (Short-run) Bidding Curves of Different Technologies



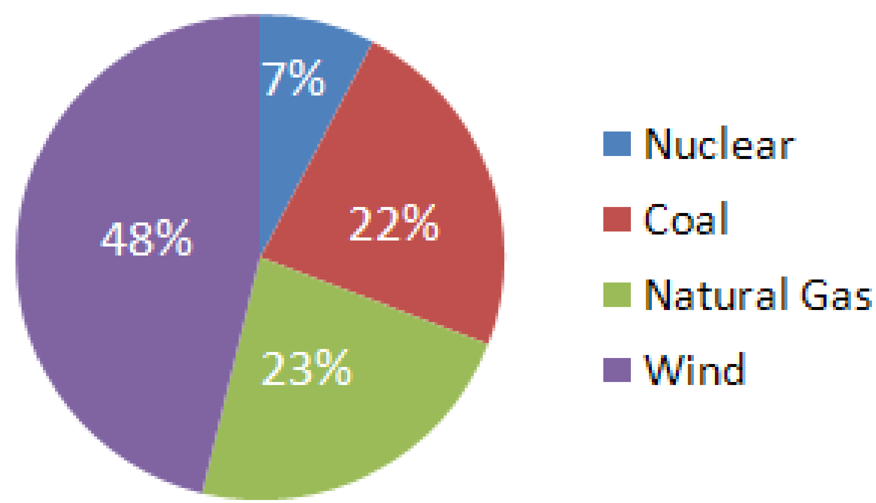

[13] M.D. Ilic, J. Joo, L. Xie and M. Prica, "A decision making framework and simulator for sustainable electric energy systems," *IEEE Transactions on Sustainable Energy* (2011).

# Numerical Experiment

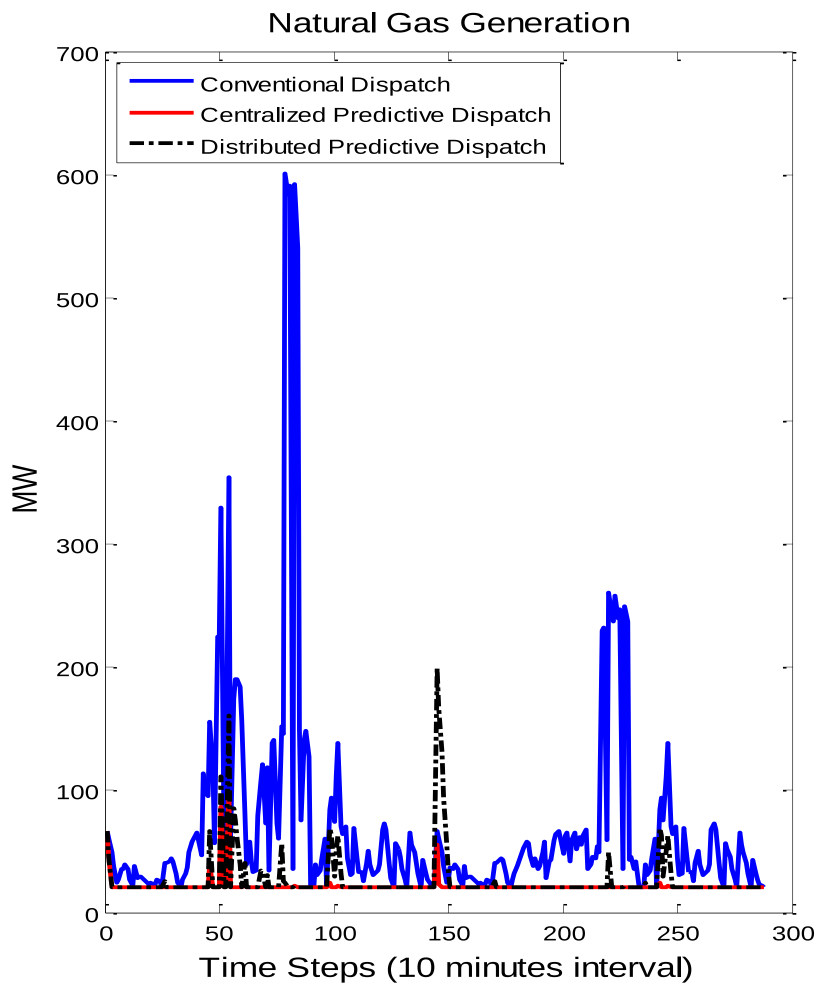


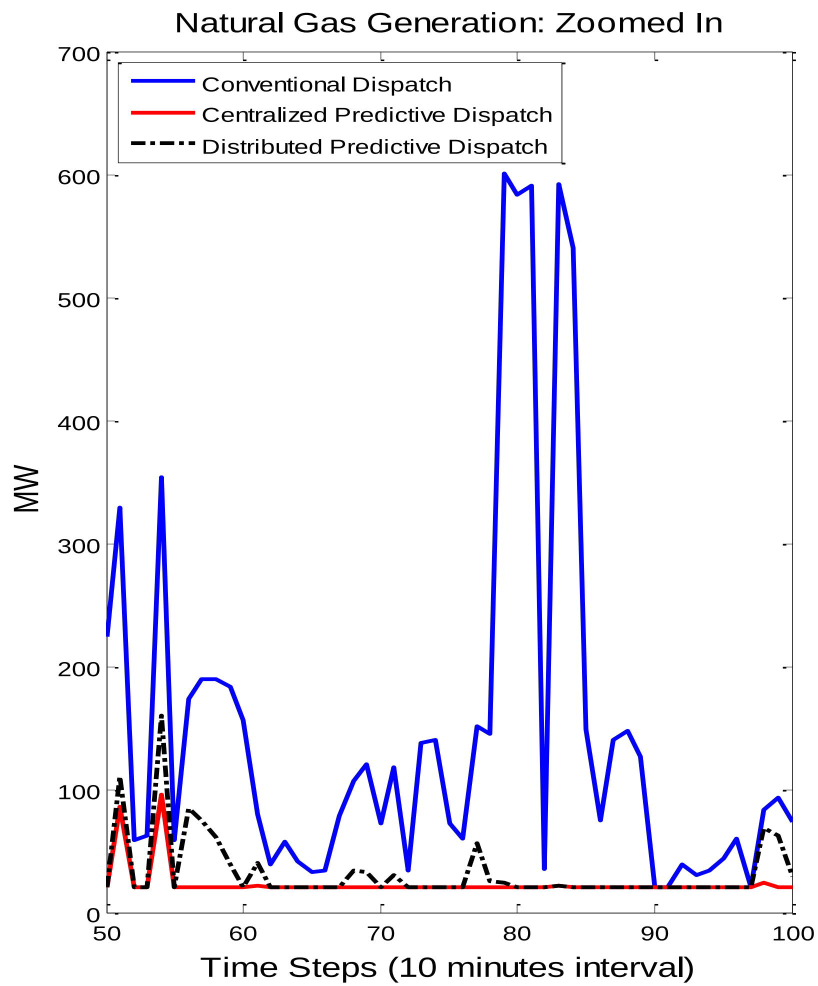

Compare (1) static dispatch with inelastic demand with (2) look-ahead coordinated with elastic demand (including 2000 aggregated PHEVs of 20kW charging power)

Total Installed Capacity: 5200 MW



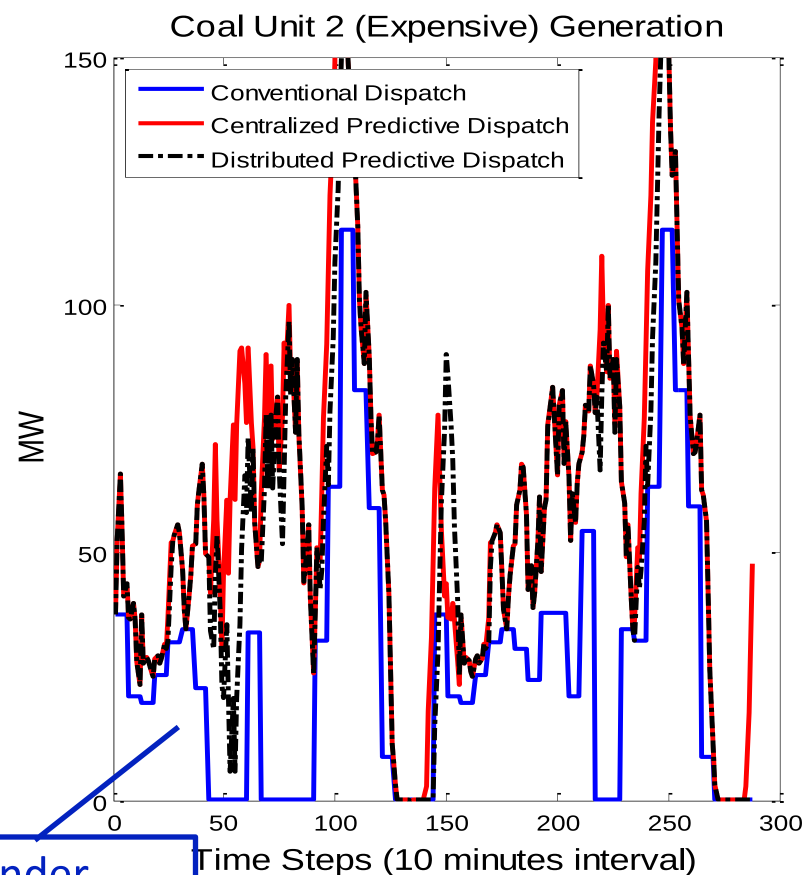
# (Fast and expensive) N.G. Outputs

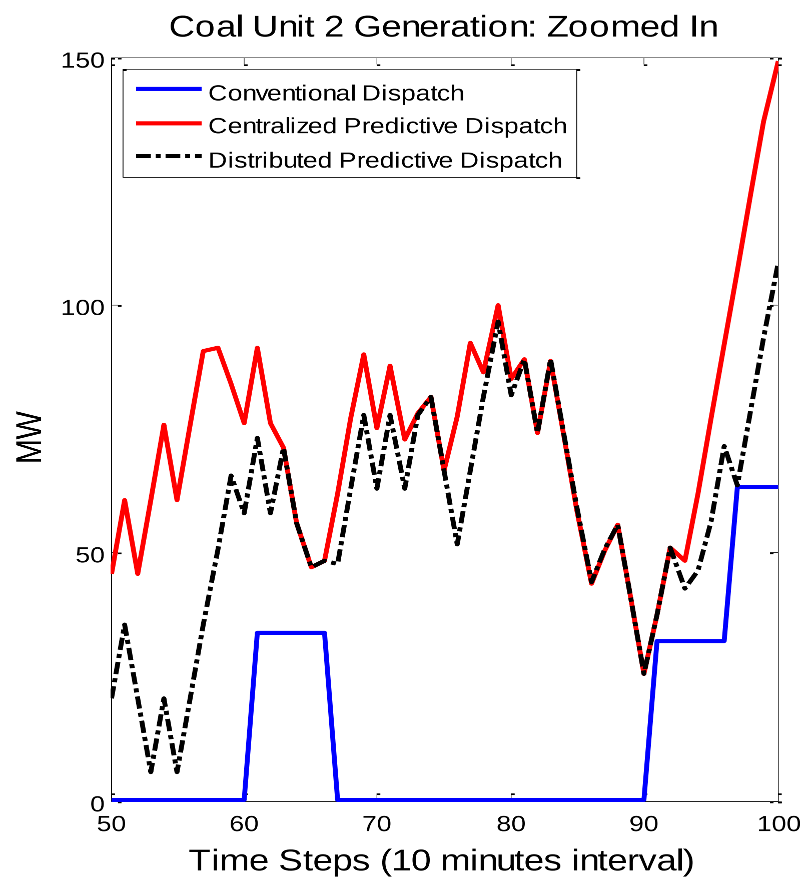



[11] Marija Ilic, Le Xie, and Jhi-Young Joo, "Efficient Coordination of Wind Power and Price-Responsive Demand Part II: Case studies", IEEE Transactions on Power Systems (accepted)

# (Slower and cheaper) Coal Utilization

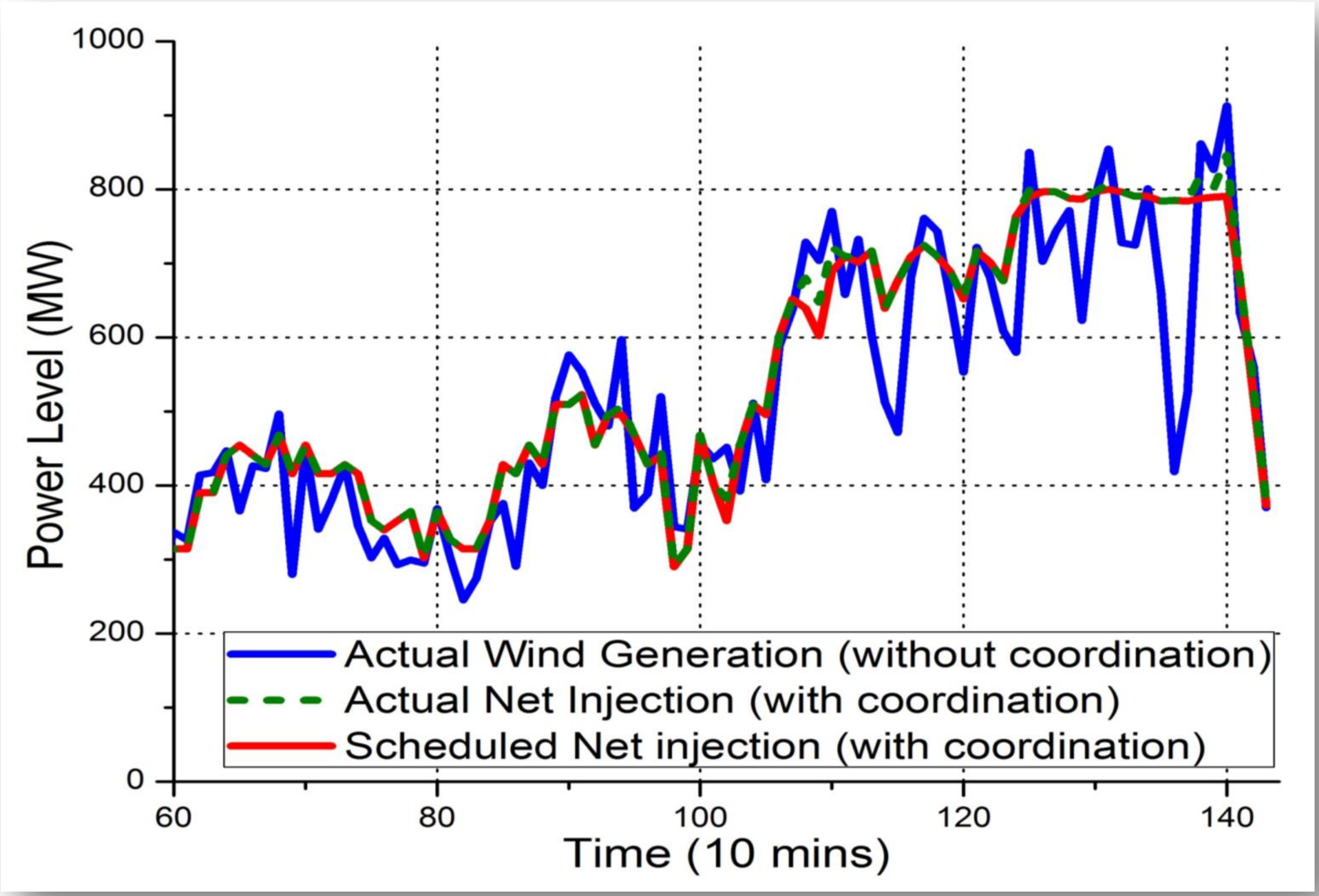



Under-utilization

[11] Marija Ilic, Le Xie, and Jhi-Young Joo, "Efficient Coordination of Wind Power and Price-Responsive Demand Part II: Case studies", IEEE Transactions on Power Systems (submitted)

# “Smoothing Out” Benefits from Coordinating PHEVs with Wind

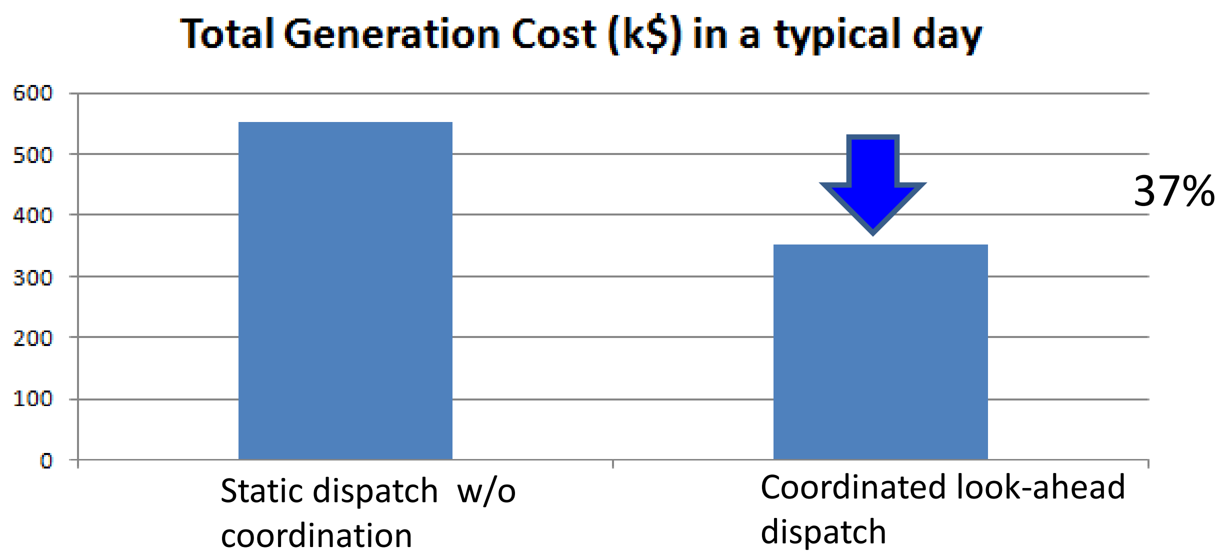


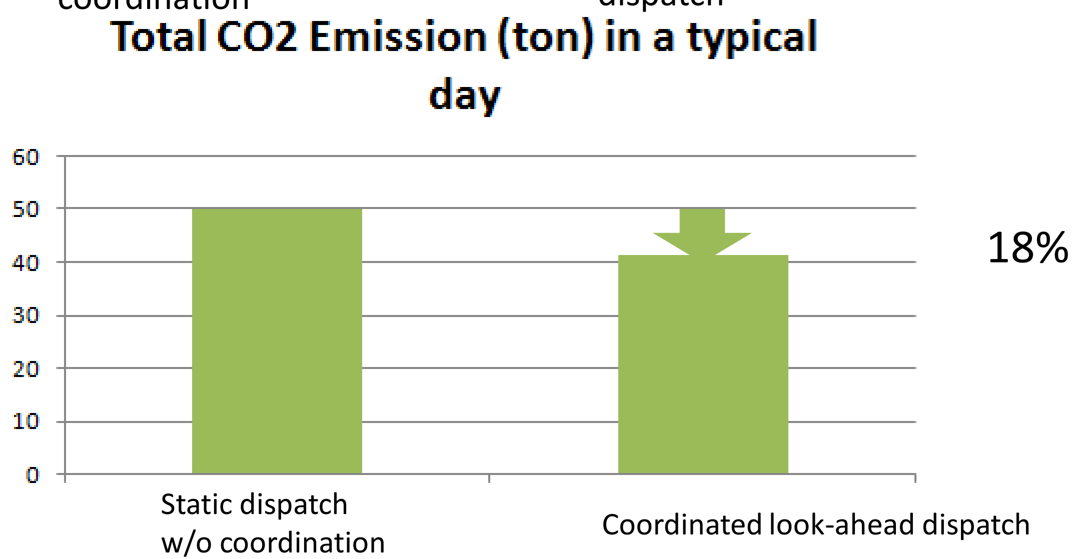


[12] L. Xie, Y. Gu, A. Eskandari, and M. Ehsani, “Fast MPC-based Coordination of Wind Power and Battery Energy Storage Systems,” *submitted to IEEE Transactions on Industrial Electronics*.

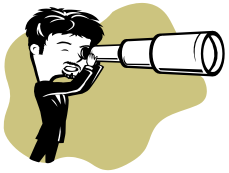
# Potential System-wide Benefits

Value of Coordinated MPC with Price Responsive Demand



# Remarks Part I



- Distributed Look-ahead dispatch
  - Lead to an overall more sustainable utilization of intermittent resources
  - Implementable in today's RTOs with minimum software upgrades
  - Implementable with various objective functions
- Ongoing work
  - Intermittent generation to provide both energy and frequency regulation services (Thatte, Zhang [14])

[12] L. Xie, Y. Gu, A. Eskandari, and M. Ehsani, "Fast MPC-based Coordination of Wind Power and Battery Energy Storage Systems," *submitted to IEEE Transactions on Industrial Electronics*.
[14] A. Thatte, F. Zhang, and L. Xie, "Coordination of Wind Farms and Flywheels for Energy Balancing and Frequency Regulation," IEEE PES General Meeting, 2011

# Part II: Distributed Stability Assessment of Linearized Power System Dynamics

Component Level

Better prediction and control of intermittent resources

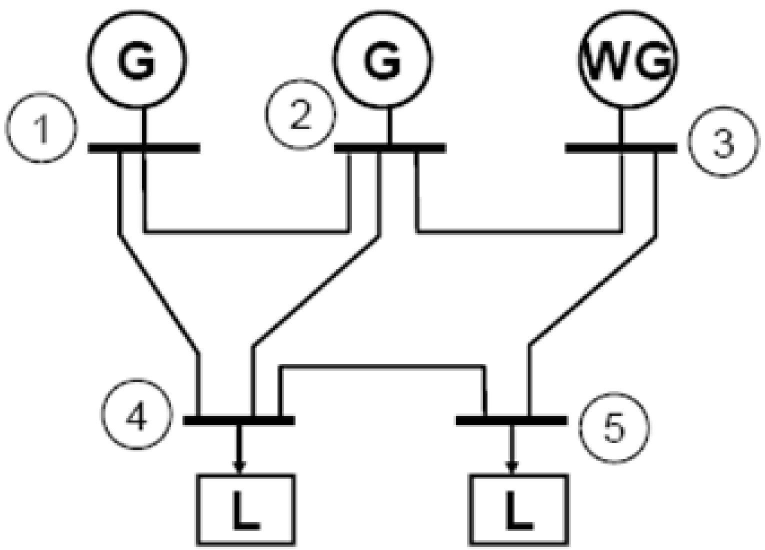
Advanced sensors, actuators and communication devices

System Level

Stable system operation with distributed intermittent resources

Reduce system cost for meeting diverse objectives with intermittent resources

# Modeling Integration of Distributed Resources

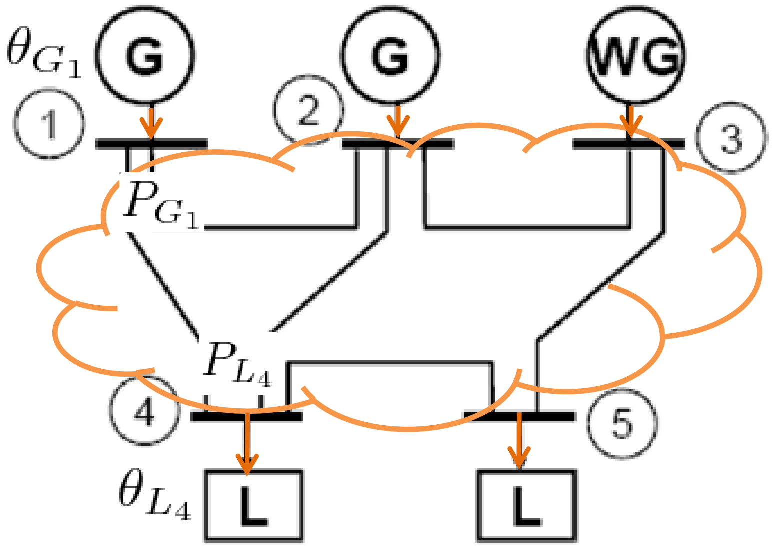



G: generator
WG: wind generator
L: load

- The structure of the dynamical model is determined by
  - *Network representation*
  - *Load models [15]*
- Conventional model:
  - Equivalenced load model
- Our proposed model:
  - *Structure-preserving* model

[15] F. Galiana, "An application of system identification and state prediction to electric load modeling and forecasting," PhD Thesis, Department of Electrical Engineering, MIT, 1971.

# Network Representation




G: generator
WG: wind generator
L: load

- Network flows follow Kirchoff's laws (algebraic) (PQ decoupled case)

$$0 = \begin{bmatrix} g_1(\theta_G, \theta_L) \\ g_2(\theta_G, \theta_L) \end{bmatrix} - \begin{bmatrix} P_G \\ P_L \end{bmatrix}$$

- Take derivative w.r.t. time [16, Ilic]

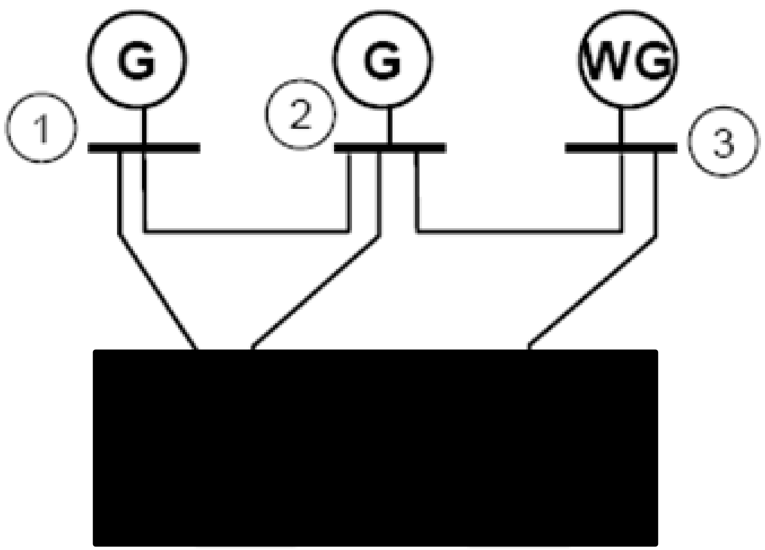
$$\begin{bmatrix} \dot{P}_G \\ \dot{P}_L \end{bmatrix} = \begin{bmatrix} \frac{\partial g_1}{\partial \theta_G} & \frac{\partial g_1}{\partial \theta L} \\ \frac{\partial g_2}{\partial \theta_G} & \frac{\partial g_2}{\partial \theta L} \end{bmatrix} \begin{bmatrix} \dot{\theta}_G \\ \dot{\theta}_L \end{bmatrix}$$

$$= \begin{bmatrix} H_{GG} & H_{GL} \\ H_{LG} & H_{LL} \end{bmatrix} \begin{bmatrix} \omega_G \\ \omega_L \end{bmatrix}$$

*H*: Power flow Jacobian Matrix Containing Structural Info.


[16] M. Ilic and J. Zaborszky, *Dynamics and Control of Large Electric Power Systems*, Wiley Interscience, 2001

# Load Models: Conventional




G: generator
WG: wind generator
L: load

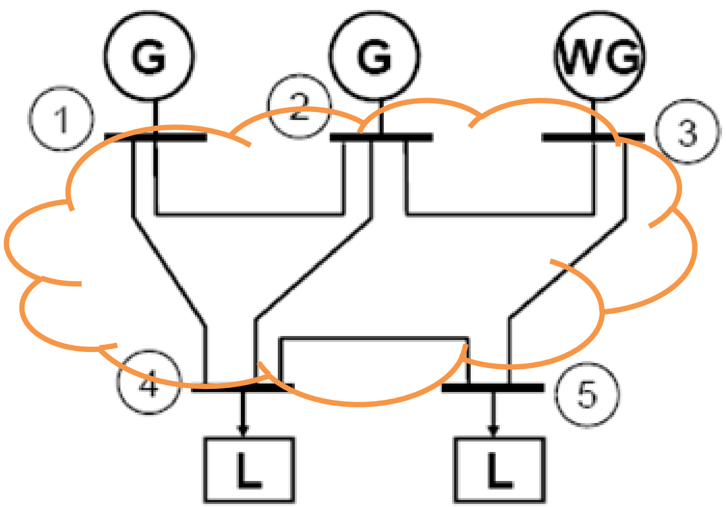
- Difficult to model from first principles
- Assume constant power load (or constant impedance)

$$\dot{P}_L = 0$$

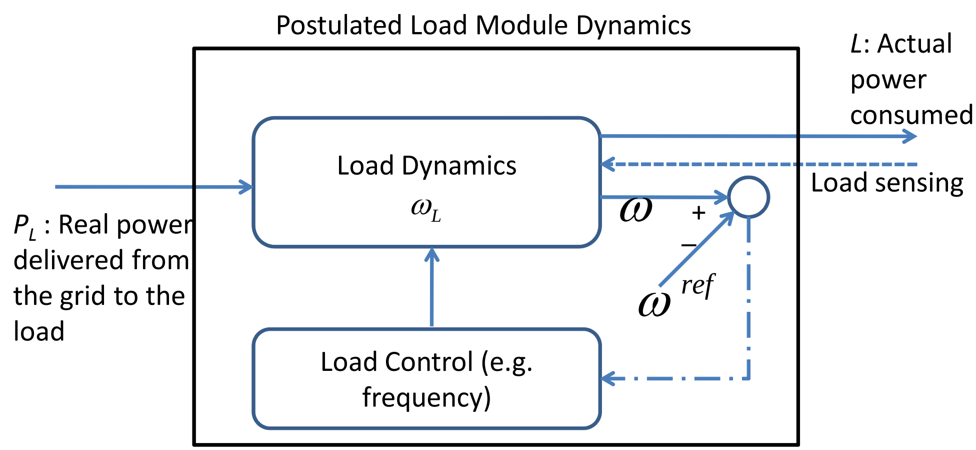
$$\dot{P}_G = (\boxed{H_{GG} - H_{LL}^{-1} H_{LG}})\omega_G$$

Dense system matrix. Graph structure is lost.

# Proposed Sensor-based Load Model




- Fast sampling data (e.g. PMUs) —> parameter identification (e.g. autoregressive methods)




[17] M. D. Ilic, L. Xie, U. A. Khan and J. M. F. Moura, "Modeling, Sensing and Control of Future Cyber-Physical Energy Systems," IEEE Transactions on Systems, Man and Cybernetics, 2010

# Structure-preserving Model of Linearized Frequency Dynamics

Modules' internal state var.

Interaction state var.

$$\begin{bmatrix} \dot{x}_G \\ \dot{x}_L \\ \dot{P}_G \\ \dot{P}_L \end{bmatrix} = \begin{bmatrix} A_G & 0 & C_G & 0 \\ 0 & A_L & 0 & C_L \\ H_{GG}E_1 & H_{GL}E_2 & 0 & 0 \\ H_{LG}E_1 & H_{LL}E_2 & 0 & 0 \end{bmatrix} \begin{bmatrix} x_G \\ x_L \\ P_G \\ P_L \end{bmatrix} + \begin{bmatrix} E_3 & 0 \\ 0 & E_4 \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} P_{T_W} \\ \mu_L \end{bmatrix} \quad (9)$$

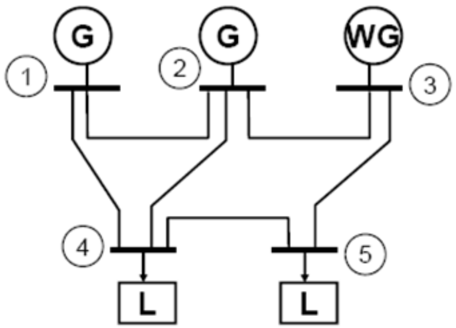
Power flow Jacobian "diluted" with many all-zero column vectors.
It preserved the structure information of the power grid

Wind mechanical torque

Random noise in AR load model

[17] M. D. Ilic, L. Xie, U. A. Khan and J. M. F. Moura, "Modeling, Sensing and Control of Future Cyber-Physical Energy Systems," IEEE Transactions on Systems, Man and Cybernetics, 2010

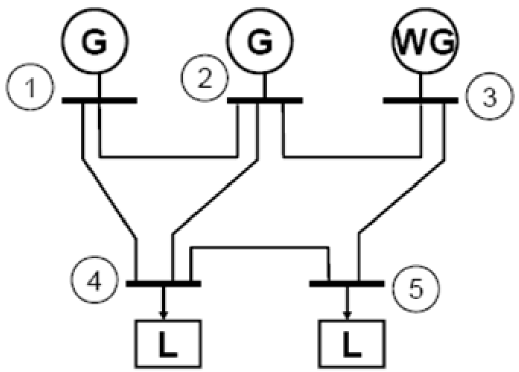
# Proposed Model on a Five Bus System




- Lossless transmission lines
- System matrix shown as below
- *Structure* of the system is *preserved*
- Model for distributed control and estimation

| | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | -1.4682 | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | -( | | | 0 | 0 |
| $x_{G1}$ | | $A_{G1}$ | 4.75 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | | $C_G$ | | 0 | 0 |
| | | | -0.2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | | | | 0 | 0 |
| | 0 | 0 | 0 | -1.468 | | 0 | 0 | 0 | 0 | 0 | 0 | | | | 0 | 0 |
| $x_{G2}$ | 0 | 0 | 0 | | $A_{G2}$ | 4.75 | 0 | 0 | 0 | 0 | 0 | | | | 0 | 0 |
| | 0 | 0 | 0 | | | -0.2 | 0 | 0 | 0 | 0 | 0 | | | | 0 | 0 |
| $x_{G3}$ | 0 | 0 | 0 | 0 | 0 | 0 | $A_{G3}$ | 0 | 0 | 0 | 0 | 0 | 0 | -0.9182 | 0 | 0 |
| $x_{L4}$ | 0 | 0 | 0 | 0 | 0 | 0 | 0 | -11. | 882 | 0 | 0 | 0 | 0 | 0 | | 0 |
| | 0 | 0 | 0 | 0 | 0 | 0 | 0 | $A_{L4}$ | -20 | 0 | 0 | 0 | 0 | 0 | $C_L$ | 0 |
| $x_{L5}$ | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | -11.7 | 82 | 0 | 0 | 0 | | 24 |
| | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | $A_{L5}$ | 20 | 0 | 0 | 0 | 0 | 0 |
| | 3.7667 | 0 | 0 | | | | 0 | -2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| $x_{net}$ | -1.6667 | 0 | 0 | | $H$ | | -1 | -1.6667 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 0 | 0 | 0 | | | | 2.5286 | 0 | 0 | -1.4286 | 0 | 0 | 0 | 0 | 0 | 0 |
| | -2 | 0 | 0 | | | | 0 | 4.3549 | 0 | -0.5882 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 0 | 0 | 0 | 0 | 0 | 0 | -1.4286 | -0.5882 | 0 | 2.1168 | 0 | 0 | 0 | 0 | 0 | 0 |

# Conventional Model




- Lossless transmission lines
- System matrix shown as below
- *Structure* of the system is *not preserved*
- Does not lend itself to distributed control and estimation

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | -1.46825 | 0.793651 | 0 | 0 | 0 | 0 | 0 | -0.7937 | 0 | 0 |
| $X_{G1}$ | 0 | -5 | 4.75 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | -4 | 0 | -0.2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| $X_{G2}$ | 0 | 0 | 0 | -1.46825 | 0.793651 | 0 | 0 | 0 | -0.7937 | 0 |
| | 0 | 0 | 0 | 0 | -5 | 4.75 | 0 | 0 | 0 | 0 |
| $X_{G3}$ | 0 | 0 | 0 | -4 | 0 | -0.2 | 0 | 0 | 0 | 0 |
| | 0 | 0 | 0 | 0 | 0 | 0 | -5.21 | 0 | 0 | -0.7937 |
| | 2.8123 | 0 | 0 | -2.4619 | 0 | 0 | -0.1894 | 0 | 0 | 0 |
| $X_{net}$ | -2.4619 | 0 | 0 | 3.7706 | 0 | 0 | -1.1579 | 0 | 0 | 0 |
| | -0.1894 | 0 | 0 | -1.1579 | 0 | 0 | 1.5269 | 0 | 0 | 0 |

# Distributed Criteria for Stability Assessment (1)

*Theorem 1:* If $A \in \Re^{n\times n}, C \in \Re^{n\times m}, H \in \Re^{m\times n}, O \in \Re^{m\times m}, O_{ij} = 0, B \in \Re^{(n+m)\times l}$, the linearized system dynamics model as below is bounded-input-bounded-state (BIBS) stable if all the following three conditions are satisfied:

$$\dot{x} = \begin{bmatrix} \dot{x}_{mod} \\ \dot{x}_{int} \end{bmatrix} = \begin{bmatrix} A & C \\ H & O \end{bmatrix} \begin{bmatrix} x_{mod} \\ x_{int} \end{bmatrix} + Bu$$

*(1) matrix $A + A^T$ is negative definite;*

*(2) matrix $CH + (CH)^T$ negative semi-definite, with $m$ nonzero eigenvalues.*

(1) condition at module level

(2) conditions at interconnection level

System-wide BIBS Stability

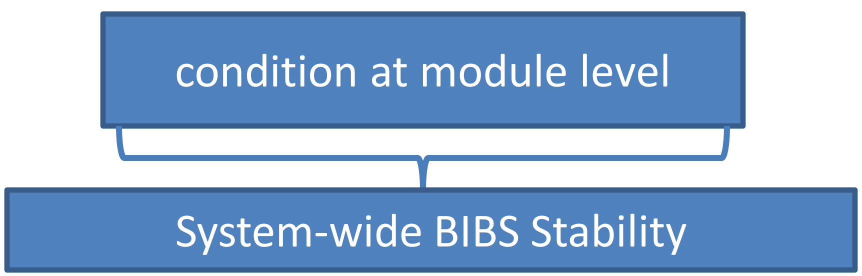
[18] L. Xie and M.D. Ilic, "Module-based interactive protocol for integrating wind energy resources with guaranteed stability." in R.R. Negenborn, Z. Lukszo, and J. Hellendoorn, editors, *Intelligent Infrastructures*, Springer, Berlin, Germany 2010.

# Distributed Criteria for Stability Assessment (2)

- Re-arrange the interaction variables into each module's internal state variables:

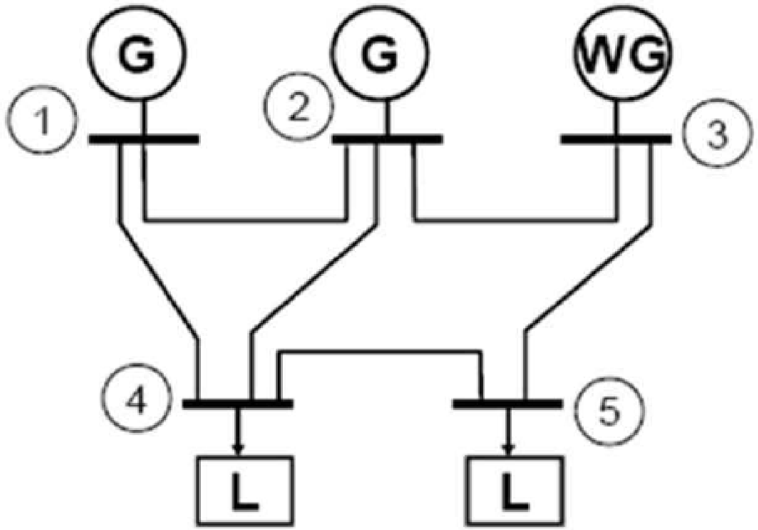
$$\dot{x}_{ia} = A_{ia}x_{ia} + \sum_{j=1,j\neq i}^{m} A_{ij}x_{ij}$$

- The system is BIBS stable if $max(Re[eig(A_ia)]) < \sum_{j=1,j\neq i}^{N} |H_{ij}|$




***"Plug-and-play" is possible***

# Example



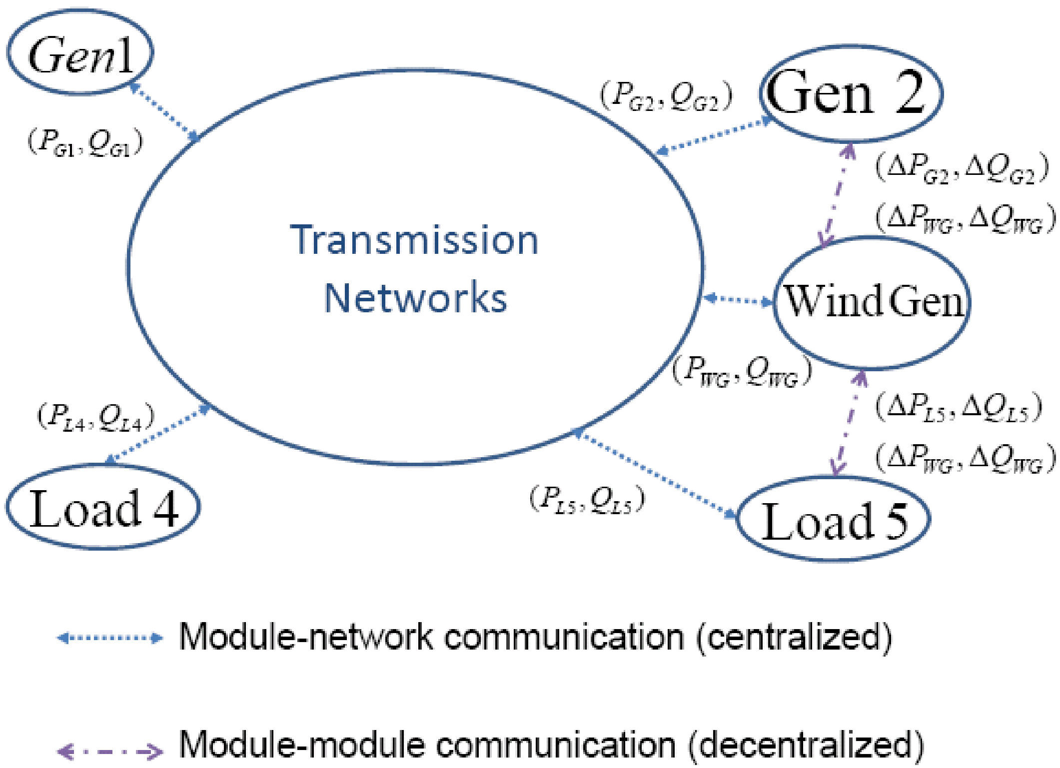

G: generator
WG: wind generator
L: load

System Matrix is Small-signal Stable

Criteria One (Distributed, Interactive): **Passed**
Criteria Two (Fully Decentralized): Not Pass

***Criteria for "Plug-and-play" is possible***
***but more conservative!***

# Communication Structure to Coordinate Linearized Dynamical Stability




- Info exchange rate: minutes
- Info exchange purpose: to guarantee the power flow Jacobian satisfy conditions (2) and in *Theorem 1*



TEXAS A&M UNIVERSITY ELECTRICAL & COMPUTER ENGINEERING

# Remarks Part II

- A structure-preserving dynamical model
  - Sensor-based dynamical load model
  - Lends itself to distributed decision making
- Sufficient criteria on small-signal stability
  - Distributed + Interactive Conditions
  - Fully Distributed Condition (more conservative)
- Interactive information protocol for coordinating online stabilization with distributed resources
  - Implementable on existing communication structure

# Summary

- Look-ahead dispatch of large-scale intermittent resources
  - Implementable in both vertically integrated and restructured industry
  - Implementable with various objective functions
- Module-based model of power system dynamics
- Criteria for distributed online assessment of linearized dynamical stability
  - Distributed + Interactive criteria
  - Fully decentralized criteria (more conservative)

# The Bigger Picture

Systems' Approach Domain Specific Knowledge

$$\underbrace{\text{Systems' Approach} \quad \text{Domain Specific Knowledge}}$$

*Role of Information* in

Future Electric Energy Systems

↓

## Smart Grid = IT + Power Grid

## + Smarter Interactions

# Acknowledgement


- Research Support from

National Science Foundation
WHERE DISCOVERIES BEGIN

Vestas

PSERC

(June 2011- 2013)

# References


[1] D.D. Siljak, Large-scale Dynamic Systems, New York: North-Holland, 1978.

[2] N.R. Sandell, P. Varaiya, M. Athans, and M.G. Safonov, "Survey of decentralized control methods for large scale systems," *IEEE Transactions on Automatic Control,* Vol. AC-23, Issue 2, pp. 108-128, Apr 1978.

[3] R. Olfati-Saber, J. A. Fax, and R. M. Murray, "Consensus and cooperation in networked multi-agent systems," *Proceedings of the IEEE,* Vol. 95, Issue 1, pp.215-233, Jan 2007.

[4] E. Muljadi and C.P. Butterfield, "Pitch-controlled variable-speed wind turbine generation," IEEE Transactions on Industry Applications, Vol. 37, Issue 1, pp.240-246, Jan 2001.

[5] A. Hering and M. G. Genton, "Powering Up With Space-Time Wind Forecasting," Journal of the American Statistical Association, Vol. 105, No. 489, pp. 92-104, March 2010.

[6] D. Gautam, V. Vittal, T. Harbour , "Impact of Increased Penetration of DFIG-Based Wind Turbine Generators on Transient and Small Signal Stability of Power Systems," IEEE Transactions on Power Systems, Vol. 24, No. 3, pp. 1426-1434, Aug. 2009

[7] F. F. Wu, K. Moslehi, and A. Bose, "Power system control centers: past, present, and future," Proceedings of the IEEE, Vol. 93, Issue 11, pp.1890-1908, Nov 2005.

[8] M. Ilic, F. Galiana, and L.Fink, Power Systems Restructuring: Engineering and Economics, Norwell, MA: Kluwer, 1998

[9] L. Xie, P. M. S. Carvalho, L. A. F. M. Ferreira, J. Liu, B. Krogh, N. Popli, and M. D. Ilić, "Integration of Variable Wind Energy in Power Systems: Operational Challenges and Possible Solutions," Proceedings of The IEEE (2011)

[10] M. Ilic, L. Xie, and J. Joo, "Efficient Coordination of Wind Power and Price-Responsive Demand Part I: Theoretical Foundations", IEEE Transactions on Power Systems (Accepted)

[11] Marija Ilic, Le Xie, and Jhi-Young Joo, "Efficient Coordination of Wind Power and Price-Responsive Demand Part II: Case Studies", IEEE Transactions on Power Systems (accepted)

[12] L. Xie, Y. Gu, A. Eskandari, and M. Ehsani, "Fast MPC-based Coordination of Wind Power and Battery Energy Storage Systems," submitted to IEEE Transactions on Industrial Electronics.

[13] M.D. Ilic, J. Joo, L. Xie and M. Prica, "A decision making framework and simulator for sustainable electric energy systems," IEEE Transactions on Sustainable Energy (2011).

[14] A. Thatte, F. Zhang, and L. Xie, "Coordination of Wind Farms and Flywheels for Energy Balancing and Frequency Regulation," IEEE PES General Meeting, 2011

[15] F. Galiana, "An application of system identification and state prediction to electric load modeling and forecasting," PhD Thesis, Department of Electrical Engineering, MIT, 1971.

[16] M. Ilic and J. Zaborszky, Dynamics and Control of Large Electric Power Systems, Wiley Interscience, 2001

[17] M. D. Ilic, L. Xie, U. A. Khan and J. M. F. Moura, "Modeling, Sensing and Control of Future Cyber-Physical Energy Systems," IEEE Transactions on Systems, Man and Cybernetics, 2010

[18] L. Xie and M.D. Ilic, "Module-based interactive protocol for integrating wind energy resources with guaranteed stability." in R.R. Negenborn, Z. Lukszo, and J. Hellendoorn, editors, Intelligent Infrastructures, Springer, Berlin, Germany 2010.

# Thank You!

*Le Xie (Lxie@ece.tamu.edu)*
*Assistant Professor*
*Department of Electrical and Computer Engineering*
*Texas A&M University*
*www.ece.tamu.edu/~lx*