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

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Outline

• Introduction
• Literature Review
• Proposed Approach and Results
  – Scheduling
  – Dynamic Stability Assessment
• Summary
Fast-Growing Intermittent Renewable Energy Resources

North American Annual Wind Installed Capacity (MW)

U.S. Annual Photovoltaic Installed Capacity (MW)

Source: Global Wind Energy Council

Source: Interstate Renewable Energy Council

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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

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
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."

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Cost of High Intermittency

Wind Power = Dirty Energy?!

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


Image source: http://itsgettinghotinhere.org/2008/04/17/wind-power-dirty-energy/
Renewable Energy
You're doing it wrong.

Source: www.wind-watch.org
Problem Statement

• Power engineering’s perspective:
  – Design efficient scheduling algorithms in support of large-scale
  \textit{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

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

What’s Needed

Component Level

Better prediction and control of variable resources

Advanced IT (sensors, actuators and communication devices)

System Level

Stable system operation with intermittent resources

Reduce system cost for meeting diverse objectives with variable resources

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Outline

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  – 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

Net Demand—No Wind

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

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

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

\[ \|\hat{L}[H]\| > \|\Delta_{LH}(t)\| \]
\[ \|\Delta_{LH}(t)\| > \|\Delta_{Lk}(t)\| \]
(Day-ahead forecast reasonably good)

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

With High Wind Penetration

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

\[ P_{Gw}(t) = \hat{P}_{Gw}[H] + \Delta_{Gw_H}(t) \]

(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)

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*

Model Predictive Control: Concept

- 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

The System Operator: Maximize Social Welfare While Observing Transmission Constraints

Supply function
\[ S_i(P_i(k+1), \lambda_i(k+1)) \]

Clearing Price
\[ \lambda_i(k), \lambda_{reg_i}(k) \]

Demand function
\[ B_j(P_{Lj}(k+1), \lambda_j(k+1)) \]

Aggregated Predictive model [3] and MPC Optimizer

Predictive Model [2] and MPC Optimizer

\[ \hat{P}_i^{max}(k+1) \]
\[ \hat{P}_i^{min}(k+1) \]
\[ \hat{\lambda}_i(k+1) \]

Generator i

\[ x_j^{max}(k+1) \]
\[ x_j^{min}(k+1) \]
\[ \hat{\lambda}_j(k+1) \]

Load j

Problem Formulation:
At Wind Generator Level

$$\text{Solve:} \max \sum_{k=1}^{K} E[\hat{\lambda}(k)(P_{G_i}(k)) - C_i(P_{G_i}(k))]$$

$$- \hat{C}_p(k)(\Delta G_i(k) - r * P_{G_i}(k))^+]$$

s.t. $$\hat{P}^{\text{max}}_{G_i}(k) = g_i(P_{G_i}(k-1), \ldots, P_{G_i}^{\text{max}}(k-N));$$

$$|P_{G_i}(k+1) - P_{G_i}(k)| \leq R_i;$$

$$P_{G_i}^{\text{min}} \leq P_{G_i}(k) \leq P_{G_i}^{\text{max}}$$

Max (Expected Profit)
Wind Forecast
Ramp Rate Constraints
Gen Capacity Constraint

Price
Power (MW)

r = 10% in ERCOT nodal market, \textit{ERCOT nodal protocols}, July 2010
At Elastic Demand Level
(e.g. Building Load Serving Entities)

\[
\begin{align*}
\min_{P_i(k)} \sum_{k=1}^{24} \left[ P_i(k) \cdot \hat{\lambda}(k) + \left\{ (x_i(k) - x_i^{\text{max}})^2 + (x_i(k) - x_i^{\text{min}})^2 \right\} \right]
\end{align*}
\]

(41)

s.t. \quad x_i(k + 1) = \varepsilon x_i(k) + (1 - \varepsilon)(T_o(k) - \gamma P_i(k))

(42)

\[ x_i^{\text{min}} \leq x_i(k) \leq x_i^{\text{max}} \text{ for all } k \]

(43)

At Storage Level (e.g. Aggregated PHEVs)

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

s.t.

\[
\begin{align*}
E (k) &= E (k-1) - P_{VG} (k) - \eta P_{avg} \\
P_{VG} (k) + P_{rup}^{cap.} (k) + P_{EX}^{cap.} (k) &= P_{max} \\
P_{VG} (k) - P_{rdn}^{cap.} (k) - P_{EX}^{cap.} (k) &= -P_{max} \\
-P_{max} &\leq P_{VG} (k) \leq P_{max} \\
E_{min} &\leq E (k) \leq E_{max}
\end{align*}
\]

Max (Expected Profit)

Energy charging dynamics

Capacity constraints

Coordinating of Wind and Battery Energy Storage System using MPC

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

Subject to

- \[ E (k) = E (k - 1) - P_{VG} (k) - \eta P_{avg} \]
- \[ P_{VG} (k) + P_{rup}^{cap} (k) + P_{EX}^{cap} (k) = P_{max} \]
- \[ P_{VG} (k) - P_{rdn}^{cap} (k) - P_{EX}^{cap} (k) = -P_{max} \]
- \[ \Delta P_{WG}^{net} (k) = \| P_{WG}^{act} (k) - P_{EX}^{act} (k) - P_{WG}^{sch} (k) \| \]
- \[ -P_{max} \leq P_{VG} (k) \leq P_{max} \]
- \[ 0 \leq E (k) \leq E_{max} \]
- \[ 0 \leq P_{EX}^{cap} \leq P_{max} \]
- \[ 0 \leq P_{rup}^{cap} \leq P_{max} \]
- \[ 0 \leq P_{rdn}^{cap} \leq P_{max} \]
- \[ P_{EX}^{act} \leq P_{EX}^{cap} \]
- \[ 0 \leq P_{WG}^{sch} (k) \leq \hat{P}_{WG}^{max} (k) \]
- \[ -P_{ramp}^{sch} \leq P_{WG}^{sch} (k + 1) - P_{WG}^{sch} (k) \leq P_{ramp}^{sch} \]

Max (Expected joint profit from energy and regulation services)

Charging/discharging dynamics

Net power injection error

Capacity constraints

Ramping constraints
Problem Formulation: At System Operator Level

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

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

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

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

\( |F(k)| \leq F^{\max} \);

\( AS(k) \geq h(\sum L_z^{\max}, \sum P_{Gw_i}^{\max}) \)
Typical (Short-run) Bidding Curves of Different Technologies

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

- Nuclear: 48%
- Coal: 7%
- Natural Gas: 22%
- Wind: 23%
(Fast and expensive) N.G. Outputs

Natural Gas Generation

- Conventional Dispatch
- Centralized Predictive Dispatch
- Distributed Predictive Dispatch

Natural Gas Generation: Zoomed In

- Conventional Dispatch
- Centralized Predictive Dispatch
- Distributed Predictive Dispatch

(Slower and cheaper) Coal Utilization

“Smoothing Out” Benefits from Coordinating PHEVs with Wind

Potential System-wide Benefits

**Total Generation Cost (k$) in a typical day**

![Bar chart comparing static dispatch w/o coordination to coordinated look-ahead dispatch, showing a 37% reduction.]

**Total CO2 Emission (ton) in a typical day**

![Bar chart comparing static dispatch w/o coordination to coordinated look-ahead dispatch, showing a 18% reduction.]

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])

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

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Modeling Integration of Distributed Resources

- 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

---

Network Representation

- 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]

\[
\begin{bmatrix}
\dot{P}_G \\
\dot{P}_L
\end{bmatrix} = 
\begin{bmatrix}
\frac{\partial g_1}{\partial \theta_G} & \frac{\partial g_1}{\partial \theta_L} \\
\frac{\partial g_2}{\partial \theta_G} & \frac{\partial g_2}{\partial \theta_L}
\end{bmatrix}
\begin{bmatrix}
\dot{\theta}_G \\
\dot{\theta}_L
\end{bmatrix}
\]

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


G: generator
WG: wind generator
L: load

H: Power flow Jacobian Matrix Containing Structural Info.
Load Models: Conventional

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

\[ \dot{P}_L = 0 \]

\[ \dot{P}_G = \left( H_{GG} - H_{LL}^{-1} H_{LG} \right) \omega_G \]

Dense system matrix. Graph structure is lost.
Proposed Sensor-based Load Model

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

G: generator
WG: wind generator
L: load

$P_L$: Real power delivered from the grid to the load

$\omega_L$: Load dynamics

Load Control (e.g. frequency)

Postulated Load Module Dynamics

$L$: Actual power consumed

Load sensing


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Structure-preserving Model of Linearized Frequency Dynamics

\[
\begin{bmatrix}
\dot{x}_G \\
\dot{x}_L \\
\dot{P}_G \\
\dot{P}_L
\end{bmatrix} =
\begin{bmatrix}
A_G & 0 & C_G & 0 \\
0 & A_L & 0 & C_L \\
H_{GG}E_1 & H_{GL}E_2 & 0 & 0 \\
H_{LG}E_1 & H_{LL}E_2 & 0 & 0
\end{bmatrix}
\begin{bmatrix}
x_G \\
x_L \\
P_G \\
P_L
\end{bmatrix}
\]

\[+ \begin{bmatrix}
E_3 & 0 \\
0 & E_4 \\
0 & 0 \\
0 & 0
\end{bmatrix}
\begin{bmatrix}
P_{TW} \\
\mu_L
\end{bmatrix}
\]

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


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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

\[
\begin{align*}
A_{G1} & = \begin{pmatrix}
-1.468 & 0 & 0 & 0 & 0 & 0 \\
0 & 4.75 & 0 & 0 & 0 & 0 \\
-0.2 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
-1 & 0 & 0 & 0 & 0 & 0
\end{pmatrix}
\\
A_{G2} & = \begin{pmatrix}
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
-11 & 0 & 0 & 0 & 0 & 0
\end{pmatrix}
\\
A_{G3} & = \begin{pmatrix}
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
-11.7 & 0 & 0 & 0 & 0 & 0
\end{pmatrix}
\\
A_{L4} & = \begin{pmatrix}
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
2.5286 & 0 & 0 & 0 & 0 & 0
\end{pmatrix}
\\
A_{L5} & = \begin{pmatrix}
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
-1.4286 & -0.5882 & 0 & 2.1168 & 0 & 0
\end{pmatrix}
\\
H & = \begin{pmatrix}
3.7667 & 0 & 0 & 0 & 0 & 0 \\
-1.6667 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
-2 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0
\end{pmatrix}
\\
C_G & = \begin{pmatrix}
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
-0.9182 & 0 & 0 & 0 & 0 & 0
\end{pmatrix}
\\
C_L & = \begin{pmatrix}
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0
\end{pmatrix}
\end{align*}
\]
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

\[
\begin{bmatrix}
-1.46825 & 0.793651 & 0 \\
0 & -5 & 4.75 \\
-4 & 0 & -0.2
\end{bmatrix}
\begin{bmatrix}
0 & 0 & 0 & 0 & -0.7937 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 \\
\end{bmatrix}
\]

\[
\begin{bmatrix}
2.8123 & 0 & 0 & -2.4619 & 0 & 0 & -0.1894 \\
-2.4619 & 0 & 0 & 3.7706 & 0 & 0 & -1.1579 \\
-0.1894 & 0 & 0 & -1.1579 & 0 & 0 & 1.5269 \\
\end{bmatrix}
\]
Distributed Criteria for Stability Assessment (1)

Theorem 1: If $A \in \mathbb{R}^{n \times n}$, $C \in \mathbb{R}^{n \times m}$, $H \in \mathbb{R}^{m \times n}$, $O \in \mathbb{R}^{m \times m}$, $O_{ij} = 0$, $B \in \mathbb{R}^{(n+m) \times l}$, 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.


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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

\[
\max(\text{Re}[\text{eig}(A_{ia})]) < \sum_{j=1, j \neq i}^{N} |H_{ij}|
\]

“Plug-and-play” is possible

condition at module level

System-wide BIBS Stability
Example

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
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

Smart Grid = IT + Power Grid
+ Smarter Interactions

Role of Information in Future Electric Energy Systems

Systems’ Approach  Domain Specific Knowledge
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References

Thank You!

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