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- **Ph.D.** (2006), Illinois Institute of Technology
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# **Research Interests**

- Power Systems Optimization and Economics
   Modeling of HVDC Transmission System
   Energy Infrastructure Interdependencies
   Smart Grid
- **Renewable Energy Application**

# **Research Projects**

- American Transmission Company, Waukesha, WI (2007-2008)
- □ ISO-New England, Holyoke, MA (2006-2007)
- □ Siemens Energy Automation, Minneapolis, MN. (2005)
- □ Nexant Corporation, San Francisco, CA. (2002-2004)



# **Computational Aspects in Managing Electricity Infrastructure**

**February 9, 2009** 



# Outline

- Power System Economics and Security
- **Galaxies Security-Constrained Unit Commitment**
- Optimal Scheduling of Generation Resources
- **Optimal Control of HVDC Transmission Systems**
- **Application Software**



# **I.** Power System Economics and Security



## **U** Vertically Integrated Utility





### **Restructured Power System**





# □ Security ! Security ! Security !



### □ Hierarchical Power System Analysis





# **II. Security-Constrained Unit Commitment**



### Security-Constrained Unit Commitment (SCUC)?





### □ ISO (SCUC) and Market Participants





### □ SCUC Scales

Systems	# of Units	# of Bus	# of Lines	# of Load
ComED (Chicago)	169	1,168	1,474	568
METC (Michigan)	153	1,892	2,279	1,039
FPL (Florida)	98	-	-	-
ISO-NE	284	1,859	2,588	676
ERCOT	599	5,663	7,036	3,695
WECC	863	4,432	6,936	2,420
<b>Eastern Interconnection</b>	5,284	49,155	65,711	30,314



# SCUC with AC Constraints

- Objective and Constraints

*Min*  $f(\mathbf{x})$ Objective Function

- > Generation Cost
- Startup/Shutdown Cost

# Unit Commitment Constraints

- **Power balance**  $\succ$
- System spinning and operating reserve requirements >
- **Generation capacity**
- Minimum On/Off time limits >
- $\succ$ **Ramping Up/Down limits**
- **Fuel and emission limits**  $\triangleright$

#### Network Security Constraints $g2(x) \leq b2$

- **Power flow equations**
- **Transmission flow and bus voltage limits**
- Limits on control variables  $\triangleright$
- **Time limited corrective controls for contingencies**  $\succ$

 $g1(x) \leq b1$ 



# **SCUC** with AC Constraints

# - Solution (Benders Decomposition)

π

# > Original Problem

Min
$$c^T x$$
Objective $Ax \ge b$ UC Constraints $Ex+Fy \ge h$ Network Security Constraints

Initial Master Problem (UC)

$$Min$$
 $c^T x$ 
 $Ax \ge b$ 

Security Check Subproblem

*Min* 
$$w(\hat{x}) = \mathbf{1}^{T} \mathbf{s}$$
  
*S.t.*  $\mathbf{F}\mathbf{y} + \mathbf{s} \ge \mathbf{h} - \mathbf{E}\hat{\mathbf{x}}$ 

> Benders Cuts
$$w(\hat{x}) - \pi^{T} E(x - \hat{x}) \leq 0$$
> Modified Master Problem
$$Min \quad c^{T} x$$
Ax ≥ b
$$w(\hat{x}) - \pi^{T} E(x - \hat{x}) \leq 0$$



### □ SCUC with Contingency Constraints





# **SCUC Master (UC) Solution**

### Lagrangian Relaxation

 $\begin{array}{l} Min \ f(\mathbf{x}_1, \mathbf{x}_2, \cdots, \mathbf{x}_n) \\ \text{S.t.} \\ & h(\mathbf{x}_1, \mathbf{x}_2, \cdots, \mathbf{x}_n) \leq \mathbf{d} \qquad \lambda \\ & g_1(\mathbf{x}_1) \leq \mathbf{b}_1 \\ & g_2(\mathbf{x}_2) \leq \mathbf{b}_2 \\ & \vdots & \vdots \\ & g_n(\mathbf{x}_n) \leq \mathbf{b}_n \end{array} \quad \text{Original}$ 

### > Mixed Integer Programming

$$Min \mathbf{c}^T \mathbf{y} + \mathbf{d}^T \mathbf{z}$$
  
S.t.  
$$\mathbf{A}\mathbf{y} + \mathbf{E}\mathbf{z} \le \mathbf{b}$$
  
$$\mathbf{y} \ge \mathbf{0}, \mathbf{z} \in \{0, \}$$

#### **Branch-and-Cut**

 $Min f(\mathbf{x}_1, \mathbf{x}_2, \dots, \mathbf{x}_n) + \lambda^T (h(\mathbf{x}_1, \mathbf{x}_2, \dots, \mathbf{x}_n) - \mathbf{d}) \quad \text{Lagrangian Relaxation Problem}$ 



# **SCUC Subproblem Solution**

$$Min \quad w(\hat{\mathbf{i}}, \hat{\mathbf{P}}^{0}) = \sum_{b=1}^{NB} (MP1_{b} + MP2_{b}) + \sum_{b=1}^{NB} (MQ1_{b} + MQ2_{b})$$
S.t.
$$\begin{bmatrix} \mathbf{K}_{\mathbf{P}} \cdot \Delta \mathbf{P} \\ \mathbf{K}_{\mathbf{P}} \cdot \Delta \mathbf{Q} \end{bmatrix} - [\mathbf{J}\mathbf{I}] \begin{bmatrix} \Delta \theta \\ \Delta \mathbf{V} \\ \Delta \mathbf{T} \\ \Delta \mathbf{Y} \end{bmatrix} + \begin{bmatrix} \mathbf{MP1} \\ \mathbf{MQ1} \end{bmatrix} - \begin{bmatrix} \mathbf{MP2} \\ \mathbf{MQ2} \end{bmatrix} = \begin{bmatrix} \mathbf{dP}_{0} \\ \mathbf{dQ}_{0} \end{bmatrix}$$

$$\Delta P \mathbf{L} = [\mathbf{J}\mathbf{2}] \begin{bmatrix} \Delta \theta \\ \Delta \mathbf{V} \\ \Delta \mathbf{T} \\ \Delta \mathbf{Y} \end{bmatrix} \qquad \Delta Q_{\min} \leq \Delta \mathbf{Q} \leq \Delta Q_{\max} \quad \underline{\Psi}, \overline{\Psi}$$

$$-\Delta P \mathbf{L}_{\max} \leq \Delta P \mathbf{L} \leq \Delta P \mathbf{L}_{\max}$$

$$\Delta \mathbf{V}_{\min}^{c} \leq \Delta \mathbf{V}_{\max}^{c}$$

$$\Delta \mathbf{P} = \mathbf{0} \quad \pi \quad \Delta \mathbf{T}_{\min} \leq \Delta \mathbf{T} \leq \Delta \mathbf{T}_{\max} \quad \Delta \mathbf{Y}_{\min} \leq \Delta \mathbf{Y} \leq \Delta \mathbf{Y}_{\max}$$
Benders Cut
$$w(\hat{\mathbf{i}}, \hat{\mathbf{P}}) + \sum_{i=1}^{NG} \pi_{ii} (P_{ii} - \hat{P}_{ii}) + \sum_{i=1}^{NG} (\overline{\psi}_{ii} Q_{\max,i} - \underline{\Psi}_{ii} Q_{\min,i}) (I_{ii} - \hat{I}_{ii}) \leq \mathbf{0}$$



# □ SCUC with AC Constraints





### **Example 1 (Cont'd)**





# □ SCUC - Example 2 (Large Systems)

Systems	# of Units	# of Bus	# of Binary	# of Constraints	CPU
ComED (Chicago)	169	1,168	4,056	95,928	82 sec.
METC (Michigan)	153	1,892	3,672	129,552	75 sec.
FPL (Florida)	98	-	2,352	18,888	20 sec.
ISO-NE	284	1,859	6,816	161,328	110 sec.
ERCOT	599	5,663	14,376	419,856	4 min.
WECC	863	4,432	20,712	438,600	7 min
Eastern Interconnection	5,284	49,155	126,816	3,771,384	130 min



# **III. Optimal Scheduling of Generation Resources**



# □ SCUC with Generation Resources







## **Combined – Cycle Unit**





### **Wind-Storage Unit**





# **IV. Optimal Control of HVDC Transmission Systems**



### **SCUC** with Transmission Components





### □ Market Clearing with HVDC





# SCUC with AC/DC Transmission Systems Example (3-bus system)



![](_page_29_Picture_0.jpeg)

# **V. Application Software**

![](_page_30_Picture_0.jpeg)

# Visualization of Power System Application

![](_page_30_Figure_2.jpeg)

![](_page_31_Picture_0.jpeg)

# **Wind Units in USA**

![](_page_31_Figure_2.jpeg)

![](_page_32_Picture_0.jpeg)

# > Electricity Price

![](_page_32_Figure_2.jpeg)

![](_page_33_Picture_0.jpeg)

# **Publications**

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□ Y. Fu, M. Shahidehpour and Z. Li, "Security-Constrained Unit Commitment with AC Constraints," *IEEE Transactions on Power Systems*, Vol. 20, No. 3, pp. 1538-1550, Aug. 2005

 M. Shahidehpour, W. F. Tinney and Y. Fu, "Impact of Security on Power Systems Operation," *Proceedings of the IEEE*, Vol. 93, No. 11, pp. 2013-2025, Nov. 2005

■ M. Shahidehpour, Y. Fu and T. Wiedman, "Impact of Natural Gas Infrastructure On Electric Power Systems," *Proceedings of the IEEE*, Vol. 93, No. 5, pp. 1042-1056, May 2005

■ M. Shahidehpour and Y. Fu, "Benders Decomposition — Applying Benders Decomposition to Power Systems," *IEEE Power & Energy Magazine*, Vol. 3, No. 2, pp. 20-21, Mar./Apr. 2005

 Y. Fu, Z. Li and M. Shahidehpour, "Profit-Based Generation Resource Planning," *IMA Journal of Management Mathematics*, Vol. 15, No. 4, pp. 273-289, 2004

![](_page_34_Picture_0.jpeg)

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□ J. H. Roh, M. Shahidehpour and Y. Fu "Market-based Coordination of Transmission and Generation Planning," *IEEE Transactions on Power Systems*, Vol. 22, No. 4, pp. 1406-1419, November 2007

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❑ Y. Fu, M. Shahidehpour and Z. Li, "AC Contingency Dispatch based on Security-Constrained Unit Commitment," *IEEE Transactions on Power Systems*, Vol. 21, No. 2, pp. 897-908, May 2006

![](_page_35_Picture_0.jpeg)

- ❑ Y. Fu, Z. Li, M. Shahidehpour, T. Zheng and E. Litvinov "Coordination of Midterm Outage Scheduling with Short-term Security-Constrained Unit Commitment," IEEE Transactions on Power Systems, 2008 (National Science Foundation under grant # ECCS-0725666) (under review)
- □ Y. Fu, M. Shahidehpour, J. Guo and Z. Li, "Effective Solution Algorithm Selection of Security-Constrained Unit Commitment," *IEEE Transactions on Power Systems*, 2008 (under review)
- □ J. Guo, Y. Fu, Z. Li and M. Shahidehpour, "A Direct Calculation of Line Outage Distribution Factors," *IEEE Transactions on Power Systems*, 2008 (under review)
- Liu, M. Shahidehpour, Y. Fu and Z. Li, "Security-Constrained Unit Commitment with Natural Gas Transmission Constraints," *IEEE Transactions on Power Systems*, 2008 (under review)
- L. Choobbari, M. Shahidehpour and Y. Fu, "Security-Constrained Unit Commitment with AC/ DC Transmission Constraints," *IEEE Transactions on Power Systems*, 2008 (under review)
- L. Choobbari, M. Shahidehpour and Y. Fu, "A Complete VSC-HVDC Transmission Line Model for Security-Constrained Unit Commitment," *IEEE Transactions on Power Systems*, 2008 (under review)

![](_page_36_Picture_0.jpeg)

# **Questions ?**

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