THE RELIABILITY ASSESSMENT PROJECT

George Gross
University of Illinois at Urbana–Champaign
PSERC Tele–Seminar
March 6, 2007

© copyright George Gross, 2007
OUTLINE

- Review: scope and objectives
- Principal results
- Major findings
- Showcase study: Quantification of Market Performance as a Function of System Security
THE ACADEMIC PROJECT TEAM

- George Gross, UIUC Project Leader
- Sakis Meliopoulos, Georgia Inst. of Technology
- Richard Schuler, Cornell University
- Chanan Singh, Texas A&M University
THE INDUSTRY ADVISORS

- Ali A. Chowdhury, MidAmerican Energy
- Dale Krummen, AEP
- Eugene Litvinov, ISO New England
- Philip Hsiang, California ISO
- Mahendra Patel, PJM Interconnection,
- Tom Schmehl / Bob De Mello, New York ISO
SCAPE OF THE PROJECT

- Evaluation of reliability in the wider sense of adequacy and security of bulk power systems and in the context of uncertainty management
- Explicit consideration of the numerous and various changes under restructuring
- Capability to address the scale of grid reliability issues associated with the push toward grid regionalization
KEY OBJECTIVES

- To improve the representation of congestion situations in reliability evaluation
- To enhance the composite system modeling for reliability analysis through the explicit representation of operational considerations and economic aspects
- To develop computationally efficient tools for reliability evaluation of large systems
- To explicitly couple the reliability assessment with the analysis of the corresponding economics
PRINCIPAL RESULTS

- An improved understanding of the impacts of congestion on bulk power reliability
- An explicit evaluation of the impacts on system reliability of remedial actions and protection system hidden failures
- A useful scheme in security evaluation for the detection of island formation and the identification of causal factors under multiple line outages
PRINCIPAL RESULTS

- An explicit evaluation of the impacts of different security criteria on the market performance economics thereby providing the benefit/cost justification for a selected security criterion
- Design of a short-term resource adequacy program which takes into account both the physical and market factors that impact reliability
- Development of planning tools to optimally site generation resources taking into account congestion impacts
The ability to detect island formation and identify the outaged lines that are the causal factors is a very useful tool in system security assessment online and off-line.

The demonstrated ability of the quadratized power flow in contingency simulation and effects analysis enabled the development of enhanced tools for reliability study.
MAJOR FINDINGS

- The new approach for the systematic evaluation of economic impacts of a selected security criterion indicates that a power system may be operated under a stricter criterion without adversely impacting the economic efficiency of markets.

- The value of electricity purchased, typically, far exceeds the average price paid; as such, the value of lost load exceeds, by many times, the price paid for electricity.
MAJOR FINDINGS

- The reliability of electricity supplied over a network in terms of unanticipated interruptions and voltage and frequency stability have certain *public good* attributes, and therefore a central authority must establish their desired level.
- In most cases, the provision of reliability-enhancing services may be decentralized and left to market forces with the prices paid to suppliers reflecting the proper values of public good aspects.
MAJOR FINDINGS

- A carrots-and-sticks based approach for short-term resource adequacy is able to overcome some key deficiencies in the implemented schemes.
- The importance of including outage costs in expansion planning has been clearly demonstrated with the advances in the location techniques proposed.
MULTI-AREA SYSTEM SECURITY: THE ECONOMIC IMPACTS OF SECURITY CRITERION SELECTION

Teoman Güler
University of Illinois at Urbana–Champaign

PSERC Tele–Seminar

March 6, 2007
CONTEXT OF THE PROBLEM

- Steady-state system security
- Assessment of the performance of Day-Ahead Markets (DAM) and bilateral transactions
- Large-scale networks with multi-area systems
- Basic principle: the emulation of the way the RTO manages the system and market operations
OUTLINE

- Overview of the problem
  - physical network and DAM
  - role of security criterion
- Market performance quantification of a system snapshot
- Proposed approach
- Application study: the ISO-NE DAM
- Concluding remarks
SYSTEM AND MARKET OPERATIONS
Power system security is the ability of the system to provide electricity with the appropriate quality under normal and disturbance conditions.

Power system security is an instantaneous condition: it is a function of time and of the robustness of the system with respect to imminent disturbances, referred as contingencies.

In security applications, we refer to the disturbances of interest as contingencies.
SECURITY FRAMEWORK

normal states

secure

insecure

restorative states

emergency states
SECURITY FRAMEWORK

normal states

secure - insecure

restorative states

emergency states

transition due to disturbance
Deterministic criteria are used in system security assessments:

- \( n-1 \)
- \( n-2 \)

The contingency sets associated with each security criterion are:

\[
\mathcal{J}_{n-1} \supset \{ k_j : k_j \text{ is the single element contingency} \}
\]

\[
\mathcal{J}_{n-2} \supset \mathcal{J}_{n-1} \cup \{ k_j : k_j \text{ is the double element contingency} \}
\]
MULTI – AREA SYSTEMS

- Large-scale systems as encountered in RTOs consist of several areas interconnected via tie lines.
- The transfer capabilities of the tie lines may constrain the utilization of certain resources.
- The impacts of tie line outages may adversely affect system security.
TIE LINE OUTAGE IMPACTS
DOUBLE TIE LINE OUTAGES: SECURITY CONTROL
MARKET PERFORMANCE IMPACTS OF SECURITY CRITERION
SCOPE OF THE WORK

- Development of a general approach to quantify the monetary impacts of complying with a specified security criterion
- Quantification of the economic and the resource dispatch impacts of a change in security criterion
- Comparison of security control strategy impacts
- Investigation of the interactions among the areas
SYSTEM SNAPSHOT AT TIME $t$

- demand
- set of available units
- physical network
- transmission maintenance
- system parameters
- market participant behavior
MARKET ASSESSMENT FOR A SYSTEM SNAPSHOT

- We emulate the way the RTO currently operates the markets and the system.
- We quantify the market performance for a system snapshot under a specified security criterion.
- Such quantification serves as the basic building block of the proposed approach.
ASSUMPTIONS

- Unit commitment decisions fully reflect the requirements of the security criterion in force.
- Ancillary services provision and acquisition requirements under the RTO framework do not impose any additional constraints on the system.
- Bidding behavior of each market participant is independent of the security criterion in force.
MARKET ASSESSMENT FOR A SYSTEM SNAPSHOT

multi-area system

market participants

bilateral transactions

prefered seller/buyer schedule

system states and line flows

market outcomes
\[ \text{SCOPF PROBLEM FORMULATION} \]

\[
\begin{aligned}
\text{max} & \quad S \quad \sum_{k=1}^{K} \left( \sum_{j=1}^{N_k} \beta_{b_j}^{(0)} (p_{b_j}^{(0)}) - \sum_{i=1}^{N_k} \beta_{s_i}^{(0)} (p_{s_i}^{(0)}) \right) + \sum_{w=1}^{W} \alpha_w (t_w^{(0)}) \\
\text{s.t.} & \quad g^{(0)} \left( p_{s}^{(0)}, p_{b}^{(0)}, t^{(0)}, \chi^{(0)}, \gamma^{(0)} \right) = 0 \\
& \quad h^{(0)} \left( p_{s}^{(0)}, p_{b}^{(0)}, t^{(0)}, \chi^{(0)}, \gamma^{(0)} \right) \leq 0 \\
& \quad g^{(j)} \left( p_{s}^{(j)}, p_{b}^{(j)}, t^{(j)}, \chi^{(j)}, \gamma^{(j)} \right) = 0 \\
& \quad h^{(j)} \left( p_{s}^{(j)}, p_{b}^{(j)}, t^{(j)}, \chi^{(j)}, \gamma^{(j)} \right) \leq 0 \\
& \quad \left| p_s^{(j)} - p_s^{(0)} \right| \leq \Delta p_s^{(j)} \\
& \quad \left| p_b^{(j)} - p_b^{(0)} \right| \leq \Delta p_b^{(j)} \\
& \quad \left| t^{(j)} - t^{(0)} \right| \leq \Delta t^{(j)} \\
& \quad j \in J_c
\end{aligned}
\]
**SCOPF PROBLEM FORMULATION**

\[
\begin{align*}
\max \quad & \sum_{k=1}^{K} \left( \sum_{j=1}^{N^k} \beta_{b_j^k} \left( p_{b_j^k}^{(0)} \right) - \sum_{i=1}^{N^k} \beta_{s_i^k} \left( p_{s_i^k}^{(0)} \right) \right) + \sum_{w=1}^{W} \alpha_w \left( t_w^{(0)} \right) \\
\text{s.t.} \quad & g^{(0)} \left( p_s^{(0)}, p_b^{(0)}, t^{(0)}, \chi^{(0)}, \gamma^{(0)} \right) = 0 \quad \leftrightarrow \quad \lambda^{(0)} \\
& h^{(0)} \left( p_s^{(0)}, p_b^{(0)}, t^{(0)}, \chi^{(0)}, \gamma^{(0)} \right) \leq 0 \quad \leftrightarrow \quad \mu^{(0)}_h \\
& g^{(j)} \left( p_s^{(j)}, p_b^{(j)}, t^{(j)}, \chi^{(j)}, \gamma^{(j)} \right) = 0 \quad \leftrightarrow \quad \lambda^{(j)} \\
& h^{(j)} \left( p_s^{(j)}, p_b^{(j)}, t^{(j)}, \chi^{(j)}, \gamma^{(j)} \right) \leq 0 \quad \leftrightarrow \quad \mu^{(j)}_h \\
& \left| p_s^{(j)} - p_s^{(0)} \right| \leq \Delta p_s^{(j)} \quad \leftrightarrow \quad \mu_{s}^{(j)} \\
& \left| p_b^{(j)} - p_b^{(0)} \right| \leq \Delta p_b^{(j)} \quad \leftrightarrow \quad \mu_{b}^{(j)} \\
& \left| t^{(j)} - t^{(0)} \right| \leq \Delta t^{(j)} \quad \leftrightarrow \quad \mu_{t}^{(j)} \end{align*}
\]

\( j \in \mathcal{J}_e \)
MARKET PERFORMANCE METRICS

\[
S_{ce} = \sum_{k=1}^{K} S^k_{ce}
\]

\[
S^k_{ce} = \sum_{i=1}^{N^k} \left[ \beta_{b_i}^k \left( p_{b_i}^* \right) - \beta_{s_i}^k \left( p_{s_i}^* \right) \right]_{ce}
\]

\[
P_{ce} = \sum_{k=1}^{K} \sum_{i=1}^{N^k} \left[ p_{b_i}^* + \sum_{w=1}^{W} t_w^* \right]_{ce}
\]

\[
P^k_{ce} = \sum_{i=1}^{N^k} \left[ p_{s_i}^* - p_{b_i}^* + \sum_{w=1}^{W} t_w^* - \sum_{i=m_w \in N^k} t_w^* \right]_{ce}
\]
QUANTIFICATION OF SECURITY CRITERION CHANGE IMPACTS

SCOPF under security criterion \( C \)

system operations

market operations

market outcomes

performance impacts

SCOPF under security criterion \( C' \)

system operations

market operations

market outcomes
CHANGES OVER TIME

- demand
- set of available units
- physical network
- transmission maintenance
- system parameters
- market participant behavior
MULTIPLE SNAPSHOT EXTENSION

- We apply the snapshot conceptual structure to each hour of the representative days for each specified criterion.
- We quantify the hourly impacts and quantify the system and area-wide $ as well as $MW$ impacts on a daily, monthly and period basis.
- The daily figures also serve to evaluate key statistics for each month such as mean, variance and range.
PROPOSED APPROACH SUMMARY

- The proposed approach quantifies the monetary impacts of complying with a specified security criterion.
- This approach is deployed to simulate the hourly decision in the DAM: key idea in the simulation is the emulation of the way the RTO manages the system and market operations.
- The proposed approach can be used to study a specified period of time.
APPLICATION EXAMPLE:
ISO–NE DAM

- We illustrate the application of the proposed approach on the ISO–NE DAM to quantify the performance impacts of operating the system under different system security criteria.

- We use the historical day–ahead data – the system model and the bids/offers submitted – with the actual market clearing methodology.
ISO–NE

Boston/Northeast Massachusetts: $A^1$
Connecticut: $A^2$
Southwest Connecticut: $A^3$
Norwalk/Stamford: $A^4$
Export: $A^5$
ISO-NE DAM

- 2005 average DAM LMPs:
  - 90 $/MWh
  - 80 $/MWh
  - 70 $/MWh

- 280 + participants
- 350 generators
- 31,000 + MW installed capacity
- Peak demand: 26,885 megawatts on July 27, 2005

THE SCOPE OF THE ISO–NE STUDY

- Contingencies: transmission line outages
- Studied criteria:

<table>
<thead>
<tr>
<th>security criterion</th>
<th>contingencies</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>single element</td>
</tr>
<tr>
<td>$C_1$</td>
<td>preventive</td>
</tr>
<tr>
<td>$C_0$</td>
<td>preventive</td>
</tr>
<tr>
<td>$C_2$</td>
<td>preventive</td>
</tr>
</tbody>
</table>

- Study period: July 2005 – May 2006, 118 DAM representative days
TOTAL DEMAND OF THE BIDS

**aggregate hourly “fixed demand”**

**aggregate hourly “price sensitive demand”**
THE BIDDING PATTERN OF A SINGLE LARGE BUYING ENTITY

aggregate hourly fixed demand
aggregate hourly price sensitive demand

no fixed demand component

regime $\mathcal{R}_1$

regime $\mathcal{R}_2$
THE $C_0$ CLEARED QUANTITIES

$MW$

26,000
24,000
22,000
20,000
18,000
16,000
14,000
12,000
10,000
8,000

25,638
16,967
9,177

23,281 maximum
15,421 average
8,733 minimum

regime $R_1$  regime $R_2$
IMPACTS ON CLEARED QUANTITIES

\( \Delta P_{c_1} \)

\( \Delta P_{c_2} \)

\begin{align*}
\mathcal{R}_1 & : 
\begin{align*}
\text{max.} & : 961 \\
\text{avg.} & : 141 \\
\text{min.} & : -646 \\
\end{align*} \\
\mathcal{R}_2 & : 
\begin{align*}
\text{max.} & : 913 \\
\text{avg.} & : 8 \\
\text{min.} & : -485 \\
\end{align*}
\end{align*}

\begin{align*}
\mathcal{R}_1 & : 
\begin{align*}
\text{max.} & : 868 \\
\text{avg.} & : 42 \\
\text{min.} & : -836 \\
\end{align*} \\
\mathcal{R}_2 & : 
\begin{align*}
\text{max.} & : 714 \\
\text{avg.} & : 184 \\
\text{min.} & : -694 \\
\end{align*}
\end{align*}
AREA – WIDE NET INJECTION IMPACTS: $C_1$ wrt. $C_0$
AREA – WIDE NET INJECTION IMPACTS: $\mathcal{C}_2$ wrt. $\mathcal{C}_0$
DAILY SOCIAL WELFARE UNDER THE CRITERION $\mathcal{C}_0$

The results are normalized by the average social welfare under reference criterion $\mathcal{C}_0$.
DAILY MARKET EFFICIENCY IMPACTS

The results are normalized by the average social welfare under reference criterion $C_0$.
CHANGES IN THE AREAS’ S CONTRIBUTIONS: $c_1$ wrt. $c_0$

The results are normalized by the average social welfare under reference criterion $c_0$. The diagram shows the changes in the areas' contributions over different months for regimes $R_1$ and $R_2$.
CHANGES IN THE AREAS' $S^C$ CONTRIBUTIONS: $C_2$ wrt. $C_0$

The results are normalized by the average social welfare under reference criterion $C_0$. The graph shows changes in areas' contributions over time, with different regimes $R_1$ and $R_2$.
REMARKS

- The increased import capabilities arising from the relaxation of the security criterion from $\mathcal{C}_0$ to $\mathcal{C}_1$ are utilized leading to higher market efficiencies.

- On the other hand, the decreased import capabilities due to security criterion change from $\mathcal{C}_0$ to $\mathcal{C}_2$ may lower the market efficiencies.
The price responsive regime $R_2$ leads to a strong attenuation of the economic impacts of changing security criterion to either $C_1$ or $C_2$.

The economic efficiency of the electricity markets need not decrease when a power system is operated under a stricter criterion as long as there is effective price-responsive demand and appropriate control actions are deployed.
POSSIBLE APPLICATIONS OF THE PROPOSED APPROACH

- Justification by the RTO of the decision to modify the security criterion to be used
- Costs/benefits analysis of network improvements to mitigate the market performance impacts of a set of specified contingencies
- Formulation of the control actions for specific contingencies
SUMMARY

- We develop a general approach to quantify the monetary impacts of complying with a specified security criterion.
- We illustrate an application of the proposed approach on the ISO-NE DAM.
- Our investigation provides important insights into the role of price responsive demand and that of the security control actions.