Impacts of Demand Response on Power Systems With High Penetration of Wind Generation

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Outline

• Introduction
• Impacts of Incentive-Based Demand Response in Day-Ahead Market
• Impacts of Price-Based Demand Response in Real-Time Market
• Conclusions
There is growing evidence that the aging electricity grid subjects us to more frequent system failures today, which will no longer be acceptable.

Smart grid is a response to economic, security, and environmental mandates placed on energy supply and delivery.

- Accommodates all generation and storage options
- Enables active participation by consumers
- Enables network autonomy and self-healing
- Provides power quality for the range of needs in a digital economy
- Optimizes asset utilization and operating efficiency
- Anticipates and responds to system disturbances in a self-healing manner
- Operates resiliently against physical and cyber attacks, and natural disasters

!!! MORE UNCERTAINTIES AND VOLATILITIES !!!
Definition of DR

- Changes in electric usage by end-use customers from their normal consumption patterns in response to changes in the price of electricity.
Definition of DR

• Changes in electric usage by end-use customers from their normal consumption patterns in response to changes in the price of electricity

• Two types of DR program:
  – Price-based DR programs
    • time-of-use pricing
    • critical peak pricing
    • variable peak pricing
    • real-time pricing
  – Incentive-based DR programs
    • direct load control
    • interruptible/curtailable service
Renewable Energy Integration - Wind

Correlation between wind and load profiles

Wind volatility and intermittency
Renewable Energy Integration - Wind

• This situation will be harmful to power systems
  – Negative LMPs may not be able to cover operation costs of generators
    • Power companies are continually making decisions to ramp down their power generations instead of selling excess energy at prices that are not profitable
    • Wind power companies would prefer to curtail wind generation. Wind energy can not be fully utilized
  – Congestion--Building more transmission lines in order to enhance the effective utilization of renewable energy (primarily wind)
Proposed Formulation

• Objective: Minimize operation costs for all generating units, including electric generation cost and start up / shut down costs

• Unit commitment constraints
  – Power balance
  – System reserve requirements
  – Generation capacity
  – Minimum ON/OFF time limits
  – Ramping UP/DOWN limits
  – Fuel and emission limits
  – ...

• Network security constraints

• DR load constraints

• LMP calculations and limitations— KKT conditions
DR Formulation

- DR Load could be scheduled for reduction or payback

$$(1 - \alpha_{dt}) \cdot D_{dt} \cdot I_{dt} + D_{dt} \cdot (1 - I_{dt}) \leq P_{dt} \leq D_{dt} + \sum_{\tau \neq t} r_{d\tau,t} \cdot \alpha_{d\tau} \cdot D_{d\tau} \cdot (1 - I_{dt})$$
Numerical Examples

• 4-bus system
  – Case 1: The traditional SCUC without load shifting
  – Case 2: The proposed model with load shifting

**GENERATOR INFORMATION**

<table>
<thead>
<tr>
<th>Unit</th>
<th>Pmin (MW)</th>
<th>Pmax (MW)</th>
<th>No Load Cost ($)</th>
<th>Startup Cost ($)</th>
<th>Segment Price ($/MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>G1</td>
<td>80</td>
<td>400</td>
<td>30</td>
<td>50</td>
<td>12</td>
</tr>
<tr>
<td>G2</td>
<td>30</td>
<td>100</td>
<td>40</td>
<td>60</td>
<td>10</td>
</tr>
</tbody>
</table>

**HOURLY WIND AND LOAD INFORMATION (MW)**

<table>
<thead>
<tr>
<th>Hour</th>
<th>L1 (fixed load)</th>
<th>L2 (shiftable load)</th>
<th>Available Wind</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>200</td>
<td>30</td>
<td>80</td>
</tr>
<tr>
<td>2</td>
<td>320</td>
<td>100</td>
<td>80</td>
</tr>
</tbody>
</table>
Numerical Examples

- Operation cost of Case 1 is $6090, and is $5990 for Case 2.

**Generation Dispatch (MW)**

<table>
<thead>
<tr>
<th>Hour</th>
<th>Wind</th>
<th>G1</th>
<th>G2</th>
<th>L1</th>
<th>L2</th>
<th>Wind</th>
<th>G1</th>
<th>G2</th>
<th>L1</th>
<th>L2</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>70</td>
<td>160</td>
<td>0</td>
<td>200</td>
<td>30</td>
<td>80</td>
<td>160</td>
<td>0</td>
<td>200</td>
<td>40</td>
</tr>
<tr>
<td>2</td>
<td>80</td>
<td>280</td>
<td>60</td>
<td>320</td>
<td>100</td>
<td>80</td>
<td>280</td>
<td>50</td>
<td>320</td>
<td>90</td>
</tr>
</tbody>
</table>

**LMP ($/MWh)**

<table>
<thead>
<tr>
<th>Bus</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hour 1</td>
<td>0</td>
<td>12</td>
<td>0</td>
<td>-12</td>
<td>12</td>
<td>12</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>Hour 2</td>
<td>10</td>
<td>12</td>
<td>10</td>
<td>8</td>
<td>10</td>
<td>12</td>
<td>10</td>
<td>8</td>
</tr>
</tbody>
</table>
Financial Stability of DR Consumers

- Consumer payment may increase after load shifting

Load profiles with respect to different DR participation levels

LMPs with respect to different DR participation levels
Financial Stability of DR Consumers

• This situation will be harmful to power systems
  – It will definitely diminish consumers’ enthusiasm to participate into DR programs since consumer payment is increased
  – The system will loss flexibility

• The objective of this research
  – Shifting the proper amount of load from peak hours to off peaks
    • Alleviating possible congestions
    • Ensuring the consumer payment will not increase after load shifting
Proposed Formulation

• **Objective:** Minimize operation costs for all generating units, including electric generation cost and start up / shut down costs

• **Unit commitment constraints**
  – Power balance
  – System reserve requirements
  – Generation capacity
  – Minimum ON/OFF time limits
  – Ramping UP/DOWN limits
  – Fuel and emission limits
  – …

• **Network security constraints**

• **DR Load constraints**

• **LMP calculations and limitations** – KKT conditions

• **Consumer payment constraints**

\[
\sum_{t=1}^{NT} LMP_{b,t} \cdot D_{ls,t} \leq \alpha_{ls} \cdot \text{payment}_{ls}
\]
Numerical Examples

- 6-bus system
  - Case 1: The traditional NCUC without load shifting.
  - Case 2: The NCUC model with load shifting.
  - Case 3: The proposed model with consumer payment requirement--MINLP

**Generator Information**

<table>
<thead>
<tr>
<th>Unit</th>
<th>Pmin (MW)</th>
<th>Pmax (MW)</th>
<th>Startup Cost ($)</th>
<th>c ($/h)</th>
<th>b ($/MWh)</th>
<th>c ($/MW²h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>G1</td>
<td>100</td>
<td>220</td>
<td>100</td>
<td>177</td>
<td>13.5</td>
<td>0.00045</td>
</tr>
<tr>
<td>G2</td>
<td>10</td>
<td>100</td>
<td>200</td>
<td>130</td>
<td>30</td>
<td>0.001</td>
</tr>
<tr>
<td>G3</td>
<td>10</td>
<td>50</td>
<td>0</td>
<td>137</td>
<td>17.7</td>
<td>0.005</td>
</tr>
</tbody>
</table>

**Load Information (MW)**

<table>
<thead>
<tr>
<th>Hour</th>
<th>L1</th>
<th>L2</th>
<th>L3</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>34</td>
<td>68</td>
<td>68</td>
</tr>
<tr>
<td>2</td>
<td>56</td>
<td>112</td>
<td>112</td>
</tr>
</tbody>
</table>
Numerical Examples

RESULTS OF LOAD SHIFTING AND COSTS

<table>
<thead>
<tr>
<th></th>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operation Cost ($)</td>
<td>8856.49</td>
<td>8054.74</td>
<td>8108.00</td>
</tr>
<tr>
<td>L2 Load Payments ($)</td>
<td>5791.91</td>
<td>6163.03</td>
<td>4999.12</td>
</tr>
<tr>
<td>L2 Load Shifting (MWh)</td>
<td>0</td>
<td>20.00</td>
<td>17.77</td>
</tr>
<tr>
<td>L3 Load Payments ($)</td>
<td>5420.98</td>
<td>5751.13</td>
<td>4732.72</td>
</tr>
<tr>
<td>L3 Load Shifting (MWh)</td>
<td>0</td>
<td>20.00</td>
<td>20.00</td>
</tr>
</tbody>
</table>

RESULTS OF LMPs ($/MWh)

<table>
<thead>
<tr>
<th></th>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bus 4 Hour 1</td>
<td>13.64</td>
<td>19.45</td>
<td>13.64</td>
</tr>
<tr>
<td>Bus 4 Hour 2</td>
<td>43.43</td>
<td>43.22</td>
<td>43.21</td>
</tr>
<tr>
<td>Bus 5 Hour 1</td>
<td>13.64</td>
<td>18.81</td>
<td>13.64</td>
</tr>
<tr>
<td>Bus 5 Hour 2</td>
<td>40.12</td>
<td>39.93</td>
<td>39.93</td>
</tr>
</tbody>
</table>
Impacts of Price-based DR in Real-Time Market

• Price-sensitive DR load levels will change in response to dynamic real-time electricity prices.
• The changes in DR loads will impact the ED schedule and in turn affect electricity market clearing prices.
• The question is whether load and/or price series will finally converge to a fixed point in a DR-integrated power system.
Price-Based DR Modeling

Function (i)
Function (ii)
Function (iii)
Function (iv)
Function (v)

$\text{DR}_{n+1}^d, \text{p.u.}$

$\text{MCP}_n^p, \text{p.u.}$
Cobweb Plot

- A diagram for quantitatively investigating the behavior of one-dimensional iterated functions

**A convergent case**

**A divergent case**
Contraction Mapping

**Definition 1** For a mapping $f : X \rightarrow X$, if there is a $x_0 \in X$ that satisfies $f(x_0) = x_0$, $x_0$ is called the fixed point of the mapping $f$.

**Theorem 1** Let $f : X \rightarrow X$ be continuously differentiable. Then $f$ is a contraction on $X$ if and only if there exists $k < 1$ with $|f'(x)| \leq k$ for all $x \in X$.

**Theorem 2** (Contraction Mapping Theorem) If $f : X \rightarrow X$ is a contraction mapping, it has a unique fixed point and the picard sequence $\{x, f(x), f(f(x)), \ldots\}$ will finally converge to the fixed point $x_0$ for all initial $x \in X$.

$$MCP^{n+1} = G(MCP^n)$$

<table>
<thead>
<tr>
<th>$\alpha$</th>
<th>0.1</th>
<th>0.2</th>
<th>0.4</th>
<th>0.8</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M'(MCP^{min})$</td>
<td>0.167</td>
<td>0.234</td>
<td>0.380</td>
<td>0.456</td>
</tr>
<tr>
<td>$M'(MCP^{max})$</td>
<td>0.548</td>
<td>0.682</td>
<td>0.876</td>
<td>1.015</td>
</tr>
<tr>
<td>$M'(MCP^{inf})$</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>MCP at the Fixed Point ($$/MWh$$)</td>
<td>30.20</td>
<td>29.47</td>
<td>28.40</td>
<td>27.51</td>
</tr>
<tr>
<td>Number of Iterations</td>
<td>6</td>
<td>6</td>
<td>7</td>
<td>N/A</td>
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<tr>
<td>Convergence Status</td>
<td>Converge</td>
<td>Converge</td>
<td>Converge</td>
<td>Diverge</td>
</tr>
</tbody>
</table>
Conclusion

• In this presentation, we analyze
  – The Impacts of incentive-based demand response on wind energy integration in day-ahead market
  – The Impacts of incentive-based demand response on consumer payment in day-ahead market
  – The Impacts of price-based demand response on real-time market clearing
References


{ Thank You! }