Primary Frequency Response Ancillary Service Market Designs

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Primary Frequency Response Ancillary Service Market Designs

Erik Ela
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Modeling, Simulation and Optimization for the 21st Century Electric Power Grid

October 24, 2012
Overview

• Motivation
  • Frequency response decline
  • Emergence of electronically-coupled new technologies without PFR capabilities
  • Present disincentives, lack of incentives, market behavior
• PFR Market Design (preliminary)
  • Market clearing engine
  • Pricing mechanism
• Case Studies (preliminary)
**Frequency**

Electrical frequency – Interconnection balance of supply and demand.

- Initial slope of decline is determined by system inertia (or cumulative inertial response of all generation).

<table>
<thead>
<tr>
<th>Time</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 s</td>
<td></td>
</tr>
<tr>
<td>typically, 5–10 s</td>
<td></td>
</tr>
<tr>
<td>typically, 20–30 s</td>
<td></td>
</tr>
<tr>
<td>typically, 5–10 min</td>
<td></td>
</tr>
</tbody>
</table>

Primary Freq. Control: AGC
Primary and Secondary Reserve

Non-event
- Regulating Reserve
  - Automatic
    - Within optimal dispatch
- Following Reserve
  - Manual
    - Part of optimal dispatch

Event
- Contingency Reserve
  - Instantaneous
    - Primary
    - Secondary
    - Tertiary
  - Replace primary and secondary
    - Stabilize Frequency
    - Return frequency to nominal and/or ACE to zero

- Ramping Reserve
  - Non-Instantaneous
    - Primary
    - Secondary
    - Tertiary
  - Replace secondary
    - Return frequency to nominal and/or ACE to zero

Decline in response

Ingleson 2010, Ingleson 2005
Decline on the Eastern Interconnection of about 60-70 MW/0.1Hz/year
Reasons:
- High governor dead bands
- Operating mode (sliding pressure)
- Blocked governors

Fig. 2. Mean Beta computed for each year from 1994 through 2009. Data are not complete for the year 1999, so that year is omitted from this plot.
Decline in response

Other issues:
Governor withdrawal
Oscillatory behavior (stepped droop curves)
Slow response
Insensitive dead bands
High renewable scenarios

Pool-based SMD: 2 settlements, locational marginal pricing, Energy is co-optimized with spinning reserve, nonspinning reserve and regulation reserve
Frequency Bias

Bias (MW/0.1Hz) is not Frequency Response (MW/0.1Hz)!!

\[ ACE = N_{IA} - N_{IS} - 10B(F_{A} - F_{S}) \]

**Scenario 1**
- \( N_{IS} = 500 \) MW
- \( F_{S} = 60 \) Hz
- \( B = -200 \) MW/0.1 Hz
- \( N_{IA} = 600 \) MW
- \( F_{A} = 60 \) Hz
- \( ACE = 100 \) MW

**Scenario 2**
- \( N_{IS} = 500 \) MW
- \( F_{S} = 60 \) Hz
- \( B = -200 \) MW/0.1 Hz
- \( N_{IA} = 600 \) MW
- \( F_{A} = 59.95 \) Hz
- \( ACE = 0 \) MW
Disincentives

3% Penalty Band over generation schedule
60 Hz system
5% Droop curve setting
0 Hz Dead band

$$\frac{1 \text{ p.u. power}}{0.05 \text{ p.u. frequency}} = \frac{0.03 \text{ p.u. power}}{X \text{ p.u. frequency}}$$

$$X = 0.0015 \text{ p.u. frequency} = 90 \text{ mHz for a 60 Hz system}$$

Any deviation greater than 90 mHz, a generator automatically will be penalized with a functioning turbine governor enabled!


“...this requirement provides impetus to the approach of a reward based method of monitoring and providing financial incentive for governing response. This observation is the root of the purpose of the Task Force, to address the conflicting pulls of lowest possible cost of electricity without risking the costs of a system blackout.”
Linking the reliability requirements

Nadir slope $\Delta f/\Delta t$

Max{$\Delta f/\Delta t$}

$f_{nadir}$

$t_{nadir}$

$f_{ss}$

$t_{ss}$
Scheduling

1. Ensure resources are providing enough synchronous inertia so that \( \text{Max} \ \{\Delta f/\Delta t\} \) does not exceed a limit that can cause triggering of ROCOF relays or lead to instability or triggering of UFLS

\[
\sum_{i=1}^{NG} \left(u_{lu} \ast H_i \ast S_i^{\text{max}} \right) + H_L^{eq} \ast L_c \geq i_A^{\text{req}} \ \forall t \in NT
\]

2. Ensure enough PFR capacity is available

\[
\sum_{i=1}^{NG} P1^f \geq P1^{\text{req}} - D \ast L_c \ \forall t \in NT
\]
3. Ensure PFR is sensitive enough to frequency to avoid triggering of UFLS and to limit the deviation of $f_{ss}$ from nominal, as well as limiting insensitivity
   - Equivalent droop curves to capacity based on maximal
   - Head room availability: $\chi$ – binary variable
   - Consider governor dead bands
   - Governor enablement
   - If governors are too high, they are not acceptable
4. Ensure that PFR is triggered fast enough to avoid UFLS and that it is fully deployed within a time limit \((t_{ss})\) to ensure stability and limit risk.
5. Ensure that PFR response is stable and does not cause instability or oscillatory frequency behavior.
6. Ensure a sustainable PFR, so that after reaching $f_{ss}$ there is a constant recovery with no withdrawal of PFR when secondary reserve is deployed to recover frequency.
Pricing

\[ \mathcal{L} = \sum_{i=1}^{N_{\text{B}}} C_i R_i - \lambda \times \left( \sum_{i=1}^{N_{\text{B}}} P_i - L - \text{Loss} \right) - \sum_{i=1}^{N_{\text{B}}} \left( \mu_i \times \left( \sum_{n=1}^{N_{\text{G}}} S_{F_{n,i}} \times (P_n - L_n) - PL_i \right) \right) - \psi \\
\times \left( \text{Loss} - \sum_{n=1}^{N_{\text{G}}} L_{R_n} \times (P_n - L_n) \right) - \sum_{i=1}^{N_{\text{R}}} \beta_i \times \left( \sum_{\ell=1}^{N_{\ell}} \text{Pres}_\ell - R \right) \]

\[ \text{LMP}_n = \frac{\partial \mathcal{L}}{\partial L_n} = \lambda + \sum_{i=1}^{N_{\text{B}}} \mu_i \times S_{F_{n,i}} - \lambda \times L_{R_n} \]

\[ \text{RCP} = \frac{\partial \mathcal{L}}{\partial R} = \beta \]

Pricing Hierarchy

\( \text{PFR}^{\text{nadir}} \rightarrow \)

\( \text{PFR}^{\text{SS}} \rightarrow \text{P2}^{\text{spin}} \rightarrow \text{P2}^{\text{nonspin}} \)

\( \text{PFR}^{0} \rightarrow \)
Pricing

Synchronous Inertia requirement is discrete sensitivity.

Increasing $I_{\text{req}}$ an infinitesimal has no marginal cost.

With marginal pricing concept, there is always a zero price, and no incentives to provide synchronous inertia

Hybrid pricing (NYISO) and ELMP (MISO) for energy pricing of gas turbines concept

Integrality constraint relaxed for pricing of synchronous inertia (no change in schedule)
Key concepts

- Incorporate these constraints into SCUC model using MILP
- How pricing affects revenues and uplift
- Incentivizing response that is not simply capacity
- Links to the reliability constraints needed for sufficient frequency response on the interconnection
- Applicable to systems which are part of large synchronous interconnections and isolated systems.
- Reduces uplift when resources are needed for reliability.
- True physical representation of the PFR capabilities
Test System

<table>
<thead>
<tr>
<th>Unit</th>
<th>$H (s)$</th>
<th>$R (p.u.)$</th>
<th>$DB (mHz)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>U12</td>
<td>2.6</td>
<td>0.05</td>
<td>36</td>
</tr>
<tr>
<td>U20</td>
<td>2.8</td>
<td>0.05</td>
<td>36</td>
</tr>
<tr>
<td>U50</td>
<td>3.5</td>
<td>0.05</td>
<td>36</td>
</tr>
<tr>
<td>U76</td>
<td>3.0</td>
<td>0.05</td>
<td>36</td>
</tr>
<tr>
<td>U100</td>
<td>2.8</td>
<td>0.05</td>
<td>36</td>
</tr>
<tr>
<td>U155</td>
<td>3.0</td>
<td>0.05</td>
<td>36</td>
</tr>
<tr>
<td>U197</td>
<td>2.8</td>
<td>0.05</td>
<td>36</td>
</tr>
<tr>
<td>U350</td>
<td>3.0</td>
<td>0.05</td>
<td>36</td>
</tr>
<tr>
<td>U400</td>
<td>5.0</td>
<td>0.05</td>
<td>36</td>
</tr>
</tbody>
</table>

$T_G = 0.2 \text{ s},\ T_{CH} = 0.3 \text{ s},\ T_{RH} = 7.0 \text{ s},\ F_{HP} = 0.3$

## Case Studies

<table>
<thead>
<tr>
<th>$P1_A^{Req}$ (MW)</th>
<th>$P1_A^{Nadir}$ (MW)</th>
<th>$\Delta f_{max}$ (Hz)</th>
<th>$I_A^{Req}$ (MVAs)</th>
<th>$P2^{Req}$ (MW)</th>
<th>$DB_{max}$ (Hz)</th>
<th>$t^{ss}$ (s)</th>
<th>$t^{nadir}$ (s)</th>
<th>$t^{rec}$ (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>44</td>
<td>33</td>
<td>0.2</td>
<td>5500</td>
<td>120</td>
<td>0.1</td>
<td>30</td>
<td>4</td>
<td>10</td>
</tr>
</tbody>
</table>

### Base Case Comparison

<table>
<thead>
<tr>
<th>Production Costs ($)</th>
<th>Avg. Units online</th>
<th>Avg. inertial energy (MVAs)</th>
<th>Avg. $P1^{ss}$ (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BC1</td>
<td>BC2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>568,297</td>
<td>569,315</td>
<td>8563</td>
<td>43.7</td>
</tr>
</tbody>
</table>

### 15% Wind Case Comparison

<table>
<thead>
<tr>
<th>Production Costs ($)</th>
<th>Avg. Units online</th>
<th>Avg. inertial energy (MVAs)</th>
<th>Avg. $P1^{ss}$ (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>WC1</td>
<td>WC2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>401,287</td>
<td>403,616</td>
<td>7283</td>
<td>36.75</td>
</tr>
</tbody>
</table>
Case Studies

Spin only

PFR scheduling
Uplift reduction

13% reduction in uplift
## Sensitivity to PFR characteristics

<table>
<thead>
<tr>
<th></th>
<th>Total Energy Payment ($)</th>
<th>Total PFR Payment ($)</th>
<th>Total Cost ($)</th>
<th>Total Rev. = Payment – Cost ($)</th>
<th>Change in Rev. vs. Base Case $ / %</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Base Case</strong></td>
<td>87,277</td>
<td>333</td>
<td>71,256</td>
<td>16,355</td>
<td>-</td>
</tr>
<tr>
<td><strong>Reducing R to 4%</strong></td>
<td>96,337</td>
<td>496</td>
<td>71,108</td>
<td>25,725</td>
<td>9,370 / 57%</td>
</tr>
<tr>
<td><strong>Reducing DB to 10 mHz</strong></td>
<td>93,789</td>
<td>587</td>
<td>71,089</td>
<td>23,285</td>
<td>6,932 / 42%</td>
</tr>
</tbody>
</table>
Conclusions

- Lack of incentives might be leading cause to frequency response declines
  - Ancillary service market might be logical next step with new BAL-003
- Very minor changes when incorporating PFR characteristics on today’s system
  - Change likely on blocking of governor systems and high governor dead bands
- Larger change on systems with high penetrations on PFR-incompatible resources
  - Could incentivize these resources to install capabilities
- Uplift is reduced, resources are incentivized to be online for PFR capabilities only
- Resources are incentivized for improvements for various PFR capabilities, goal of market design.
Questions?

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