Performance-Based Pricing of Frequency Regulation in Electricity Markets

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Outline

- Background and Current Practices for Procuring, Dispatching and Compensating Frequency Regulation
- Motivation for Developing a New Approach for the Frequency Regulation Service Compensation
- Proposed Methodology for Frequency Regulation Service Compensation
- Test Case and Numerical Results
- Conclusions and Directions for Further Research
Background and Current Practices

- **Frequency regulation service**: Injection or withdrawal of active power by energy resources in response to an RTO's AGC dispatch signal used to balance supply and demand on the transmission system and meet the frequency regulation needs.

- Increasing RES penetration increases the need for faster-ramping resources to provide frequency regulation.

- Traditional compensation methods, based on capacity, failed to accurately compensate faster ramping resources and provide proper incentives.

- FERC Order No. 755, Oct. 20, 2011, established a two-component (capacity and performance) compensation scheme for the provision of frequency regulation service.
Resources that provide frequency regulation are placed on AGC, and dispatched by LFC signals (in a manner of seconds)

AGC ≠ RTM (different timeframes and objectives)
Background and Current Practices

- Traditional compensation mechanisms typically include:
  - **a capacity payment** (usually based on shadow price)
  - **an energy payment** (for the net energy injected/withdrawn in/from the system)

- Other Approaches:
  - **“Mileage Payments”**: ISO-NE remunerates resources for the “distance” they travel following a dispatch signal (quality of the regulation service provided)
  - **Penalty for Accuracy**: NYISO incorporates accuracy with which a resource follows a dispatch signal
Motivation for a New Approach

- Emergence of RES increased the need for faster units.
- Compensation of regulation should be for the work performed.
- Solution: In addition to the capacity payment, a mileage payment, adjusted for performance of the unit responding to the AGC set-points.
- Currently, following FERC’s order, ISOs and RTOs proposed various methodologies for compensating for performance.
- However, there is no well-established methodology for calculating mileage payments and accuracy adjustments (each ISO submitted a different proposal on how to measure accuracy!).
Proposed Methodology

- **Frequency regulation** is procured in the Day-Ahead Market, which is formulated as a Mixed Integer Linear Programming (MILP) problem.

- Security Constrained Unit Commitment model:

  \[
  \text{Minimize } \sum_{h} \left\{ \text{Energy Cost} + \text{Ancillary Services Cost} + \text{Commitment Cost} \right\}
  \]

  subject to
  
  System Requirements / Constraints
  Resource-Specific Constraints

- Compensation for Frequency Regulation:
  - **Capacity Payments**
  - **Performance-Based Payments**
Proposed Methodology

- **Capacity Payments:**

  Reserve requirements constraints

  \[ \sum_{i} R_{i,h}^{\text{Up}} \geq R_{h}^{\text{Up, Req}} \quad \forall h \]

  \[ \sum_{i} R_{i,h}^{\text{Down}} \geq R_{h}^{\text{Down, Req}} \quad \forall h \]

  \[ \begin{align*}
  R_{i,h}^{\text{Up}} & \quad R_{i,h}^{\text{Down}} \\
  R_{h}^{\text{Up, Req}} & \quad R_{h}^{\text{Down, Req}} \\
  \end{align*} \]

  Scheduled frequency regulation up/down for resource \( i \), hour \( h \)

  Requirements for frequency regulation up/down for hour \( h \)

  Shadow prices \( \rightarrow \) Capacity Payments
Proposed Methodology

- Performance-Based Payments:

\[
\text{Mileage Payments} = \frac{\text{Actual Mileage}}{\text{MW-miles}} \times \frac{\text{Mileage Price}}{\text{MW-miles}} \times \text{Performance Score}
\]

- Up/down movement of the resource following AGC dispatch signal
- Market-based or administratively set
- Different approaches; no well-established methodology
Proposed Methodology

- **Mileage Calculations:**

  Regulation signal: \[ \hat{S}_t = S_t - B_t \]

  Telemetry range: \[ \hat{T}_t = T_t - B_t \]

  Regulation Up signal: \[ \hat{S}_{t\text{Up}} = \max\{0, \hat{S}_t\} = \max\{0, S_t - B_t\} \]

  Regulation Down signal: \[ \hat{S}_{t\text{Down}} = \left| \min\{0, \hat{S}_t\} \right| = \left| \min\{0, S_t - B_t\} \right| \]

  Instructed Mileage (Up): \[ \hat{M}_{t\text{Up}} = \left| \hat{S}_{t\text{Up}} - \hat{S}_{t-1\text{Up}} \right| \]

  Actual Mileage (Up): \[ \hat{M}_{t\text{Up}} = M_{t\text{Up}} - U_{t\text{Up}} \]

  (similarly for Down)

  At regulation interval \( t \):

  - \( S_t \) Set-point
  - \( T_t \) Tele-metered response
  - \( B_t \) Baseline point

  \( U_{t\text{Up}} \) Under-response
Proposed Methodology

- **Mileage Calculations**:
  
  At regulation interval $t$:
  
  $S_t$: Set-point
  
  $T_t$: Tele-metered response
  
  Baseline point
  
  $0, S_t - B_t$
  
  In instructed mileage (Up):
  
  $U_{t}^{\text{Up}}$: Under-response
  
  Example of under-response and need to adjust mileage calculation
  
  [Source: CAISO, 2012]
Proposed Methodology

- Performance Evaluation:
  - Measures:
    - Absolute deviation of resource’s response from dispatch signal:
      \[ D_t = \left| \hat{S}_t - \hat{T}_t \right| = \left| S_t - T_t \right| \]
    - Ratio of deviation over the regulation signal for a time period (hour \( h \)):
      \[ \delta_{h,\text{Up}} = \frac{\sum_{t \text{ in } T_h} D_{t,\text{Up}}}{\sum_{t \text{ in } T_h} \hat{S}_{t,\text{Up}}} \]
        (similarly for regulation down)

By definition \( \delta \geq 0 \); \( \delta = 0 \): perfect performance.

The higher the value of \( \delta \) the worse the performance; it could be \( \delta > 1 \).

...transform this ratio using a sigmoid function to obtain a performance coefficient \( \eta \)...

Proposed Methodology

- **Performance Evaluation:**
  - **Measures:**

    Performance coefficient (score):

    $$\eta_{h}^{Up} = f\left(\delta_{h}^{Up}\right)$$

    where $f(\cdot)$ a sigmoid function

    Now $0 \leq \eta \leq 1.$

    Adjusting the shape of the sigmoid provides adequate incentives (low, mid, high values of $\delta$)

    $$f(\delta) = \frac{\text{Erfc}(a \cdot \delta - b)}{\text{Erfc}(-b)}$$

    $\text{Erfc}(x) = 1 - \text{Erf}(x)$

    - $a=3,$ $b=0.75$
    - $a=3,$ $b=1.25$
    - $a=2.5,$ $b=1.5$
    - $a=2.5,$ $b=1.25$

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Proposed Methodology

- **Performance Evaluation:**
  - Adjust to take into account history:

  Adjusted performance score:
  \[
  \hat{\eta}_h^{Up} = (1 - k) \cdot \eta_{h, \text{Hist}}^{Up} + k \cdot \eta_h^{Up}
  \]

  where \(0 \leq k \leq 1\), and

  \[
  \eta_{h, \text{Hist}}^{Up} = \sum_{\tau \in H^-} w_{\tau}^{Up} \cdot \eta_{\tau}^{Up}
  \]

  the historical performance, which
  i) assigns more weight to more recent history, and
  ii) takes into account the actual time share of contribution within a time period

  \(w_{\tau}^{Up}: \text{weight} ; \ H^-: \text{dynamic set of (certain number of) hours prior to hour } h\)
Test Case and Numerical Results
Greek Wholesale Electricity Market

Capacity requirements and actual mileage

Regulation Up

Regulation Down
## Test Case and Numerical Results

### Capacity and mileage shares

<table>
<thead>
<tr>
<th>Unit</th>
<th>Regulation Up</th>
<th>Regulation Down</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Capacity Share</td>
<td>100%</td>
</tr>
<tr>
<td>U1</td>
<td>4.6%</td>
<td>42.2%</td>
</tr>
<tr>
<td>U2</td>
<td>8.3%</td>
<td>5.1%</td>
</tr>
<tr>
<td>U3</td>
<td>3.1%</td>
<td>3.5%</td>
</tr>
<tr>
<td>U4</td>
<td>7.1%</td>
<td>14.6%</td>
</tr>
<tr>
<td>U5</td>
<td>2.4%</td>
<td>22.2%</td>
</tr>
<tr>
<td>U6</td>
<td>0.9%</td>
<td>0.4%</td>
</tr>
<tr>
<td>U7</td>
<td>3.9%</td>
<td>7.4%</td>
</tr>
<tr>
<td>U8</td>
<td>69.7%</td>
<td>6.6%</td>
</tr>
<tr>
<td>Total</td>
<td>100%</td>
<td>100%</td>
</tr>
</tbody>
</table>

(Absolute Figures)

<table>
<thead>
<tr>
<th>MW</th>
<th>MW-miles</th>
</tr>
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<tbody>
<tr>
<td>7800</td>
<td>27466</td>
</tr>
<tr>
<td>4000</td>
<td>27857</td>
</tr>
</tbody>
</table>

(Remark: High capacity share does not imply high mileage share)

### Capacity and mileage payments (€)

<table>
<thead>
<tr>
<th>Unit</th>
<th>Regulation Up</th>
<th>Regulation Down</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Capacity Payments</td>
<td>Mileage Payments (η = 1)</td>
</tr>
<tr>
<td>U1</td>
<td>557</td>
<td>2996</td>
</tr>
<tr>
<td>U2</td>
<td>2667</td>
<td>2130</td>
</tr>
<tr>
<td>U3</td>
<td>891</td>
<td>2033</td>
</tr>
<tr>
<td>U4</td>
<td>784</td>
<td>2612</td>
</tr>
<tr>
<td>U5</td>
<td>466</td>
<td>1339</td>
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<tr>
<td>U6</td>
<td>280</td>
<td>361</td>
</tr>
<tr>
<td>U7</td>
<td>305</td>
<td>1070</td>
</tr>
<tr>
<td>U8</td>
<td>23676</td>
<td>1193</td>
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<tr>
<td>Total</td>
<td>29626</td>
<td>13734</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>MW</th>
<th>MW-miles</th>
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(Assumed administratively set price 0.5 € / MW-mile)
Test Case and Numerical Results

Values of $\delta$ per unit and per hour

Regulation Up

Regulation Down
Test Case and Numerical Results

Applied sigmoid function

\( a = 3, b = 1.25 \)

Observe values of tangent < - 1, i.e. a reduction in \( \delta \) by \( \Delta \delta \), leads to an increase in \( \eta \) by an amount equal to \( (1+\varepsilon) \Delta \delta \), \( \varepsilon > 0 \).
Increase in Mileage Payments due to achieving a higher performance (reducing $\delta$ by 10% and 20%)

<table>
<thead>
<tr>
<th>Unit</th>
<th>Regulation Up</th>
<th>Regulation Down</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>$\delta$</td>
<td>$\delta$-10%</td>
</tr>
<tr>
<td>U1</td>
<td>51.4%</td>
<td>+15.6%</td>
</tr>
<tr>
<td>U2</td>
<td>49.6%</td>
<td>+12.6%</td>
</tr>
<tr>
<td>U3</td>
<td>54.1%</td>
<td>+11.8%</td>
</tr>
<tr>
<td>U4</td>
<td>66.3%</td>
<td>+10.4%</td>
</tr>
<tr>
<td>U5</td>
<td>67.3%</td>
<td>+12.9%</td>
</tr>
<tr>
<td>U6</td>
<td>77.1%</td>
<td>+11.2%</td>
</tr>
<tr>
<td>U7</td>
<td>12.3%</td>
<td>+6.9%</td>
</tr>
<tr>
<td>U8</td>
<td>26.8%</td>
<td>+6.7%</td>
</tr>
</tbody>
</table>
Conclusions and Further Research

- Presented comprehensive methodology for the calculation of performance-based payments for frequency regulation and tested it by deploying actual AGC operational data.

- Adjusting the shape of the sigmoid enables ISOs to influence mileage payments and provide sufficient incentives to resources.

- Need to study the interaction of capacity with mileage and the impact of these revenues on the market outcome and make-whole payments.

- Further research on market-based approaches is needed:
  - separate capacity and mileage bids and constraints or composite formulation based on the weighted sum of the bids,
  - gaming opportunities arising between the capacity and the mileage payments.
Questions?

Thank you for your attention!

Relevant Work:
A. D. Papalexopoulos, and P. Andrianesis, “Performance-Based Pricing of Frequency Regulation in Electricity Markets,” *IEEE Transactions on Power Systems*, accepted for publication.