Performance-Based Pricing of Frequency Regulation in Electricity Markets

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Increasing Real-Time and Day-Ahead Market Efficiency through Improved Software
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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

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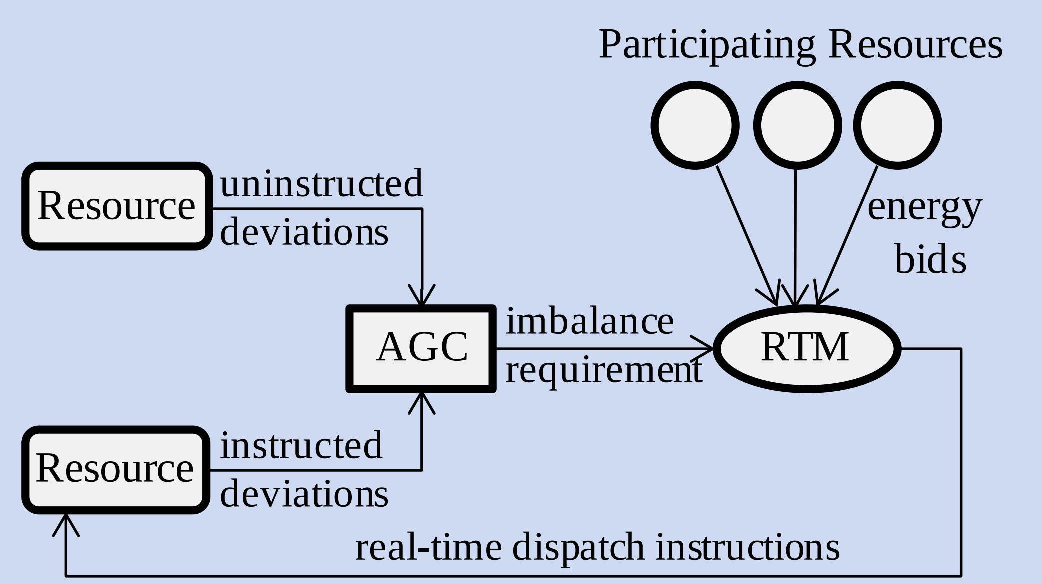
Background and Current Practices AGC and RTM Feedback Loop



- 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)

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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  - an energy payment (for the net energy injected/withdrawn in/from the system)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 started to remunerate resources for the "distance" units travel following a dispatch signal (quality of the regulation service provided)
  - Penalty for Accuracy: NYISO was the first ISO to incorporate the accuracy with which a resource follows a dispatch signal in the remuneration process

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 <u>capacity payment</u>, a <u>mileage payment, adjusted for performance</u> of the unit responding to the AGC set-points
- Currently, following FERC's order, ISOs and RTOs proposed and implemented various methodologies for compensating for performance
- However, there is no well-established methodology for calculating <u>mileage payments</u> and <u>accuracy adjustments</u>

  (*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:

$$\text{Minimize} \sum_h \left\{ \begin{pmatrix} \text{Energy} \\ \text{Cost} \end{pmatrix} + \begin{pmatrix} \text{Ancillary} \\ \text{Services} \\ \text{Cost} \end{pmatrix} + \begin{pmatrix} \text{Commitment} \\ \text{Cost} \end{pmatrix} \right\}$$

subject to

System Requirements / Constraints

Resource-Specific Constraints

- Compensation for Frequency Regulation:
  - <u>Capacity Payments</u>
  - <u>Performance-Based Payments</u>

Proposed Methodology

- Capacity Payments:

Reserve requirements constraints

$$\sum_i R_{i,h}^{\text{Up}} \geq R_h^{\text{Up, Req}} \qquad \forall h$$

$$\sum_i R_{i,h}^{\text{Down}} \geq R_h^{\text{Down, Req}} \qquad \forall h$$

Shadow prices → Capacity Payments

$R_{i,h}^{\text{Up}}$ $R_{i,h}^{\text{Down}}$ Scheduled frequency regulation up/down for resource i, hour h

$R_h^{\text{Up, Req}}$ $R_h^{\text{Down, Req}}$ Requirements for frequency regulation up/down for hour h

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Proposed Methodology

- Performance-Based Payments:

$$\begin{pmatrix}\text{Mileage}\\ \text{Payments}\\ \$\end{pmatrix} = \begin{pmatrix}\text{Actual}\\ \text{Mileage}\\ \\ \text{MW-miles}\end{pmatrix} * \begin{pmatrix}\text{Mileage}\\ \text{Price}\\ \\ \dfrac{\$}{\text{MW-miles}}\end{pmatrix} * \begin{pmatrix}\text{Performance}\\ \text{Score}\end{pmatrix}$$

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:**

At regulation interval t :

S_t Set-point

T_t Tele-metered response

B_t Baseline point

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

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

Regulation Up signal: $\hat{S}_t^{\text{Up}} = \max\left\{0, \hat{S}_t\right\} = \max\left\{0, S_t - B_t\right\}$

Regulation Down signal: $\hat{S}_t^{\text{Down}} = \left|\min\left\{0, \hat{S}_t\right\}\right| = \left|\min\left\{0, S_t - B_t\right\}\right|$

Instructed Mileage (Up): $M_t^{\text{Up}} = \left|\hat{S}_t^{\text{Up}} - \hat{S}_{t-1}^{\text{Up}}\right|$

Actual Mileage (Up): $\hat{M}_t^{\text{Up}} = M_t^{\text{Up}} - U_t^{\text{Up}}$
(similarly for Down)

U_t^{Up} Under-response

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Proposed Methodology

- Mileage Calcul…

Re…

Re…

Instruct…

Actual Mileage (Up)
(similarly for Down)

At regulation interval t :

S_t Set-point

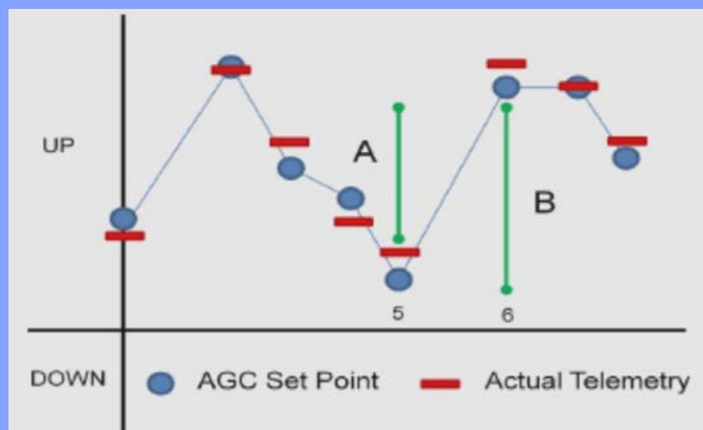
T_t Tele-metered response

Baseline point

$$0, S_t - B_t\}$$

$$n\{0, S_t - B_t\}|$$

U_t^{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):

$$\delta_h^{\mathrm{Up}} = \frac{\sum_{t \text{ in } \mathrm{T}_h} D_t^{\mathrm{Up}}}{\sum_{t \text{ in } \mathrm{T}_h} \hat{S}_t^{\mathrm{Up}}}$$

(similarly for regulation down)

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

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

…transform this ratio using a sigmoid function to obtain a performance coefficient η…

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Proposed Methodology

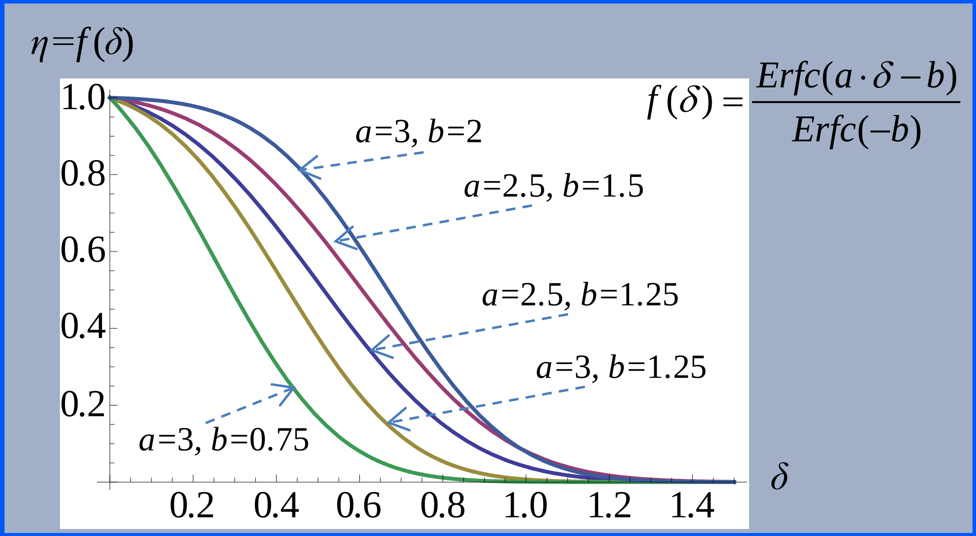
- Performance Evaluation:
  - Measures:

Performance coefficient (score): $$\eta_h^{\mathrm{Up}} = f\left(\delta_h^{\mathrm{Up}}\right)$$ (similarly for regulation down)

where $f(\cdot)$ a sigmoid function

Now $0 \le \eta \le 1$.

Adjusting the shape of the sigmoid provides adequate incentives (low, mid, high values of δ)



Proposed Methodology

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

Adjusted performance score: $$\hat{\eta}_h^{\mathrm{Up}} = (1-k)\cdot\eta_h^{\mathrm{Up,\,Hist}} + k\cdot\eta_h^{\mathrm{Up}}$$

where $0 \le k \le 1$, and

$$\eta_h^{\mathrm{Up,Hist}} = \frac{\sum_{\tau\in \mathrm{H}^-} w_\tau^{\mathrm{Up}}\cdot\eta_\tau^{\mathrm{Up}}}{\sum_{\tau\in \mathrm{H}^-} w_\tau^{\mathrm{Up}}}$$

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_τ^{Up} : weight ; H^- : dynamic set of (certain number of) hours prior to hour h

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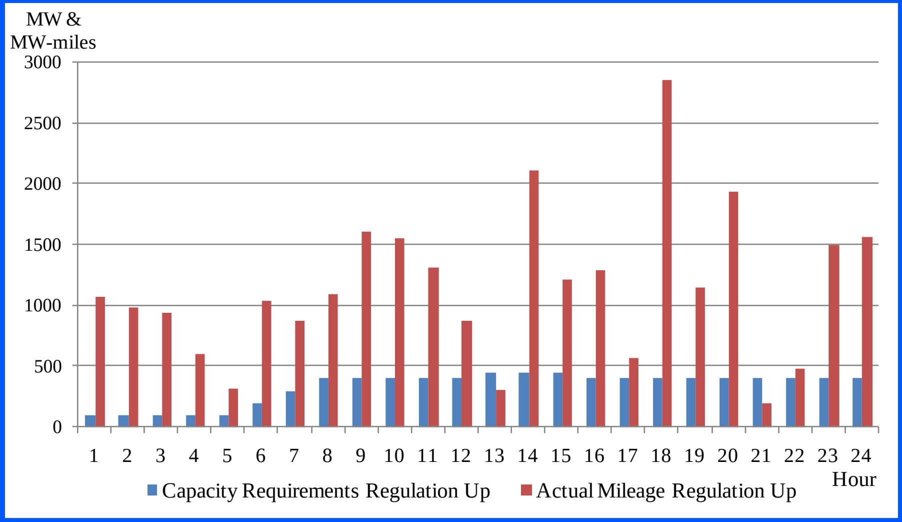
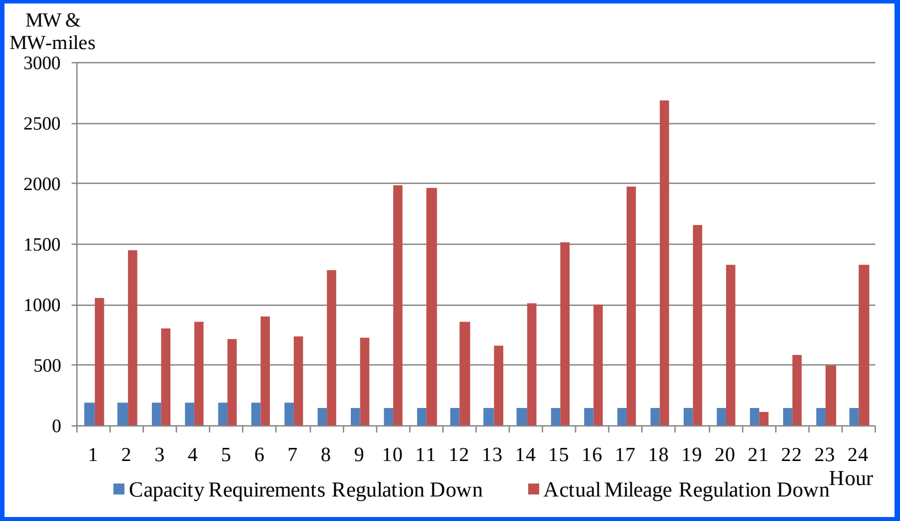
Test Case and Numerical Results Greek Wholesale Electricity Market

Capacity requirements and actual mileage



Regulation Up



Regulation Down

Capacity Requirements   Actual Mileage

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Test Case and Numerical Results

Capacity and mileage shares

	Regulation Up		Regulation Down	
Unit	Capacity Share	Mileage Share	Capacity Share	Mileage Share
U1	4.6%	21.8%	42.2%	26.3%
U2	8.3%	15.5%	7.1%	14.9%
U3	3.1%	14.8%	3.5%	11.7%
U4	7.1%	19.0%	14.6%	16.6%
U5	2.4%	9.7%	22.2%	13.6%
U6	0.9%	2.6%	0.4%	2.4%
U7	3.9%	7.8%	3.4%	7.4%
U8	69.7%	8.7%	6.6%	7.0%
Total	100%	100%	100%	100%
(Absolute Figures)	7800 MW	27466 MW-miles	4000 MW	27857 MW-miles

- Remark: High capacity share does not always imply high mileage share.

Capacity and mileage payments (€)

	Regulation Up		Regulation Down	
Unit	Capacity Payments	Mileage Payments (η = 1)	Capacity Payments	Mileage Payments (η = 1)
U1	557	2996	6285	3668
U2	2667	2130	2267	2072
U3	891	2033	385	1629
U4	784	2612	3779	2316
U5	466	1339	5597	1899
U6	280	361	136	328
U7	305	1070	819	1036
U8	23676	1193	1424	980
Total	29626	13734	20692	13928

(Assumed administratively set price 0.5 € / MW-mile)

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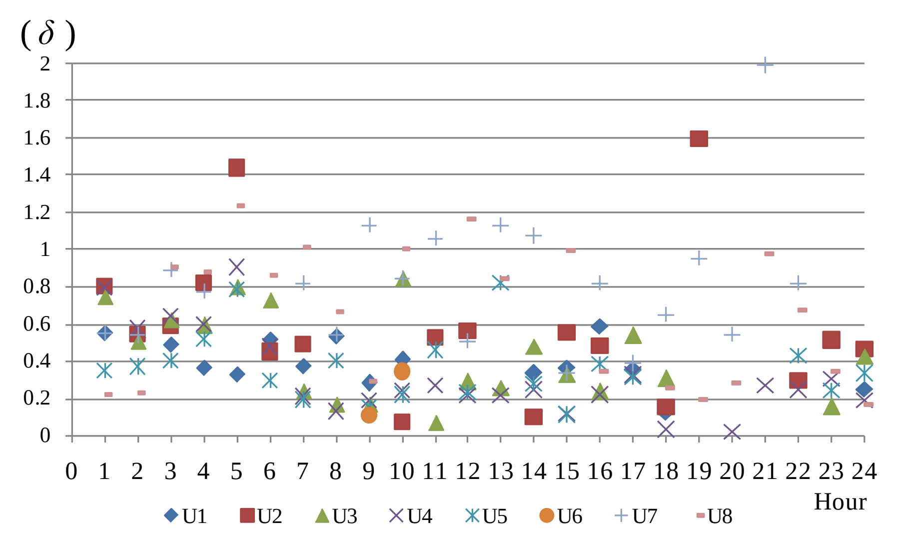
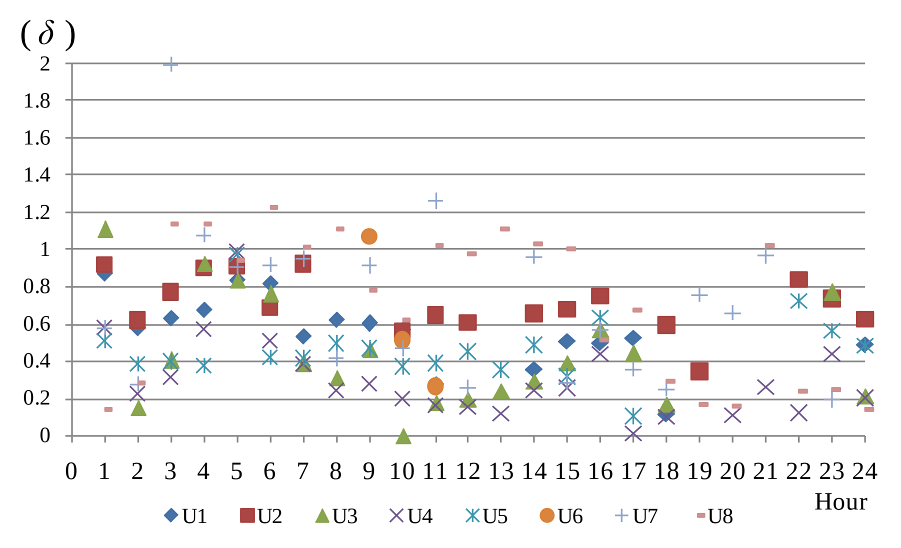
Test Case and Numerical Results

Values of δ per unit and per hour



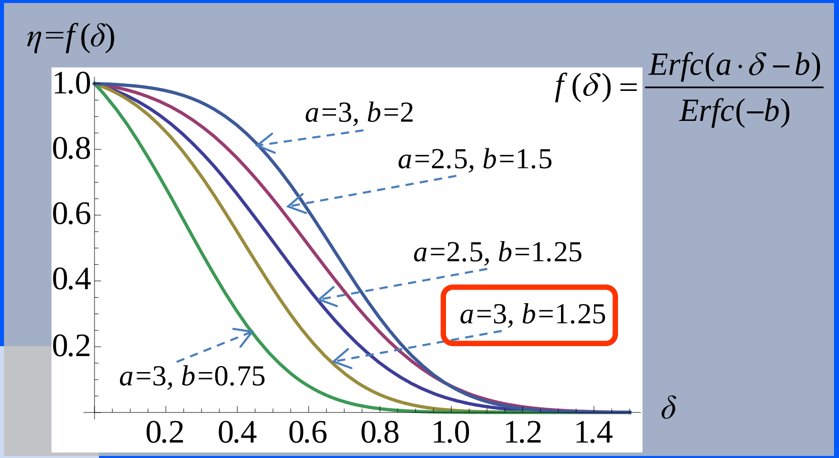
Regulation Up

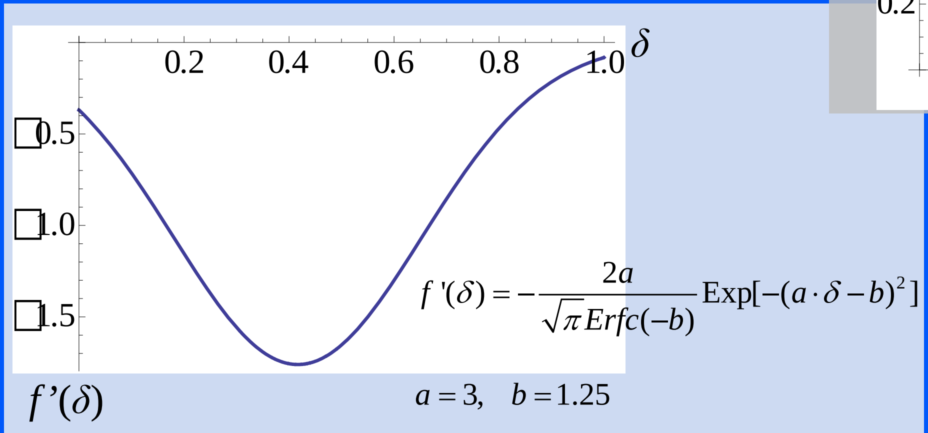


Regulation Down

Test Case and Numerical Results

Applied sigmoid function
a = 3, ***b*** = 1.25.





Derivative (tangent, i.e. slope) of the sigmoid function

Observe values of tangent < - 1, i.e. a reduction in δ by $\Delta\delta$, leads to an increase in η by an amount equal to $(1+\varepsilon)\,\Delta\delta$, $\varepsilon > 0$.

Test Case and Numerical Results

Increase in Mileage Payments due to achieving a higher performance (reducing δ by 10% and 20%)

Unit	Regulation Up			Regulation Down		
	δ	δ-10%	δ-20%	δ	δ-10%	δ-20%
U1	51.4%	+15.6%	+29.2%	28.8%	+12.7%	+26.5%
U2	49.6%	+12.6%	+24.5%	15.5%	+9.8%	+22.5%
U3	54.1%	+11.8%	+22.5%	51.0%	+11.4%	+21.2%
U4	66.3%	+10.4%	+18.5%	70.1%	+10.6%	+18.6%
U5	67.3%	+12.9%	+22.6%	45.5%	+14.3	+27.3%
U6	77.1%	+11.2%	+18.8%	48.5%	+13.7	+25.7%
U7	12.3%	+6.9%	+15.5%	25.5%	+7.9	+16.3%
U8	26.8%	+6.7%	+13.7%	31.2%	+6.6	+13.5%

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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

Conclusions and Further Research

- Market based approached for mileage payments suffer from inefficiencies due to the fact that prices for mileage are produced by the optimization software where the quantities for mileage are calculated by the AGC.
- This can lead to gaming and high bid cost recovery payments
- If bid-based methods are used then separate constraints and prices for capacity and mileage are preferable
- The key reason for the problem is the discrepancies between assumed mileage schedules resulting from the optimization and the actual mileage resulting from the AGC
- The inter-play of capacity and mileage prices and their impact on BCR payments needs further analysis

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*, Vol.29, No. 1, pp. 441-449, Jan. 2014.