PJM Regulation Market Design Senior Task Force Proposal

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Objectives

- Construct regulation products that precisely address specific critical needs of the PJM system
- Create pricing and settlements which:
  - ✓ Are transparent
  - ✓ Reasonably compensate resources for the provision of the critical service in question
  - ✓ Satisfy FERC requirements
- Avoid using products for purposes they were not designed for (e.g. the use of regulation to perform a spinning-reserve like function)
- Products should be technology agnostic

Critical Needs

Fundamentally, regulation is a ramping product and not an energy reserve product. As a result, regulation should not be expected to deliver significant net energy for sustained periods of time. From these considerations, two critical needs fall out:

- The ability for some resources to ramp quickly and frequently in response to frequency deviations and interchange imbalances on the system, which is the core function of regulation
- The ability for some resources to automatically either deliver energy to or receive energy from the system without being energy limited during times of extended pegging or net energy balance of the regulation response

Proposal of Four Products

- Regulation-Ramp-Up
- Regulation-Ramp-Down
- Regulation-Energy-Up
- Regulation-Energy-Down

Additional Comments

- Under this formulation, opaque mechanisms used to estimate the tradeoffs of resources providing the critical services, such as the Benefits Factor or the Marginal Rate of Technical Substitution, are eliminated
- Having the Regulation signals decomposed into both up and down components allows for resources to fine-tune net energy balance.
  - ✓ A battery might offer more Reg-Ramp-Down than Reg-Ramp-Up to compensate for round-trip efficiency losses.
  - ✓ An intermittent renewable energy project might only want to offer Reg-Energy-Down

List of symbols

Indices

$i \equiv$	Index corresponding to a signal tick during the current settlement interval
$j \equiv$	Index corresponding to a resource providing a service
$k \equiv$	Index corresponding to a Reg-Ramp signal neutrality interval

Regulation Signals

$\Psi(t) \equiv$	Actual regulation response in MW
$\tilde{\Psi}(t) \equiv$	Ideal regulation response in MW
$\psi_{ru}(t) \equiv$	Regulation-Ramp-Up signal, ∈ [0,1]
$\psi_{rd}(t) \equiv$	Regulation-Ramp-Down signal, ∈ [-1, 0]
$\psi_{eu}(t) \equiv$	Regulation-Energy-Up signal, ∈ [0,1]
$\psi_{ed}(t) \equiv$	Regulation-Energy-Down signal, ∈ [-1,0]
$\epsilon(t) \equiv$	Ideal regulation response deficiency in MW

Ramp Rates

$\alpha_{\tilde{r}} \equiv$	Threshold Reg-Ramp-[Up/Down] ramp rate in MW/sec
$\alpha_{\tilde{e}} \equiv$	Threshold Reg-Energy-[Up/Down] ramp rate in MW/sec
$\alpha_j \equiv$	Ramp rate in MW/sec for resource ***j***

Cleared Quantities

$Q_{ru,j} \equiv$	Reg-Ramp-Up cleared MW quantity for resource ***j***
$\tilde{Q}_{ru,j} \equiv$	Effective Reg-Ramp-Up cleared MW quantity for resource ***j***
$\tilde{Q}_{ru} \equiv$	PJM System total effective Reg-Ramp-Up cleared MW quantity
$Q_{rd,j} \equiv$	Reg-Ramp-Down cleared MW quantity for resource ***j***
$\tilde{Q}_{rd,j} \equiv$	Effective Reg-Ramp-Down cleared MW quantity for resource ***j***
$\tilde{Q}_{rd} \equiv$	PJM System total effective Reg-Ramp-Down cleared MW quantity
$Q_{eu,j} \equiv$	Reg-Energy-Up cleared MW quantity for resource ***j***
$\tilde{Q}_{eu,j} \equiv$	Effective Reg-Energy-Up cleared MW quantity for resource ***j***
$\tilde{Q}_{eu} \equiv$	PJM System total effective Reg-Energy-Up cleared MW quantity
$Q_{ed,j} \equiv$	Reg-Energy-Down cleared MW quantity for resource ***j***
$\tilde{Q}_{ed,j} \equiv$	Effective Reg-Energy-Down cleared MW quantity for resource ***j***
$\tilde{Q}_{ed} \equiv$	PJM System total effective Reg-Energy-Down cleared MW

Dispatch from Load Basepoint

$D_{ru,j}(t) \equiv$	Actual Reg-Ramp-Up dispatch MW for resource ***j*** at time ***t***
$D_{rd,j}(t) \equiv$	Actual Reg-Ramp-Down dispatch MW for resource ***j*** at time ***t***
$D_{eu,j}(t) \equiv$	Actual Reg-Energy-Up dispatch MW for resource ***j*** at time ***t***
$D_{ed,j}(t) \equiv$	Actual Reg-Energy-Down dispatch MW for resource ***j*** at time ***t***
$D_{ru}(t) \equiv$	Actual PJM System total Reg-Ramp-Up dispatch MW at time ***t***
$D_{rd}(t) \equiv$	Actual PJM System total Reg-Ramp-Down dispatch MW at time ***t***
$D_{eu}(t) \equiv$	Actual PJM System total Reg-Energy-Up dispatch MW at time ***t***
$D_{ed}(t) \equiv$	Actual PJM System total Reg-Energy-Down dispatch MW at time ***t***

Regulation-Ramp-(Up/Down)

$\lambda(t) \equiv$	Cumulative bias of the Reg-Ramp signals at time ***t***
$\tau \equiv$	Maximum time allowed for Reg-Ramp neutrality to be achieved
$\Phi(t) \equiv$	Ideal Regulation-Ramp response at time ***t***

Regulation-Energy

$\dot{\lambda}(t) \equiv$	Required Reg-Ramp neutralization rate at time ***t***
$\Lambda(t) \equiv$	Required Reg-Energy neutralization response in MW at time ***t***
$\tilde{\psi}_e(t) \equiv$	Ideal Reg-Energy signal at time ***t***, ∈ [-1,1]

Performance Scores

$\delta_{ru,j}(t) \equiv$	Desired Reg-Ramp-Up response for resource ***j*** at time ***t***
$\delta_{rd,j}(t) \equiv$	Desired Reg-Ramp-Down response for resource ***j*** at time ***t***
$\delta_{eu,j}(t) \equiv$	Desired Reg-Energy-Up response for resource ***j*** at time ***t***
$\delta_{ed,j}(t) \equiv$	Desired Reg-Energy-Down response for resource ***j*** at time
$\nu_{ru,j}(t) \equiv$	Expected Reg-Ramp-Up response for resource ***j*** at time ***t***
$\nu_{rd,j}(t) \equiv$	Expected Reg-Ramp-Down response for resource ***j*** at time ***t***
$\nu_{eu,j}(t) \equiv$	Expected Reg-Energy-Up response for resource ***j*** at time ***t***
$\nu_{ed,j}(t) \equiv$	Expected Reg-Energy-Down response for resource ***j*** at time ***t***
$\gamma_{ru,j}(t) \equiv$	Reg-Ramp-Up response deficiency for resource ***j*** at time ***t***
$\gamma_{rd,j}(t) \equiv$	Reg-Ramp-Down response deficiency for resource ***j*** at time ***t***
$\gamma_{eu,j}(t) \equiv$	Reg-Energy-Up response deficiency for resource ***j*** at time ***t***
$\gamma_{ed,j}(t) \equiv$	Reg-Energy-Down response deficiency for resource ***j*** at time ***t***

$F_{ru,j} \equiv$ Settlement Interval Reg-Ramp-Up performance score for resource ***j***

$F_{rd,j} \equiv$ Settlement Interval Reg-Ramp-Down performance score for resource ***j***

$F_{eu,j} \equiv$ Settlement Interval Reg-Energy-Up performance score for resource ***j***

$F_{ed,j} \equiv$ Settlement Interval Reg-Energy-Down performance score for resource ***j***

Settlements (Values are Specific to a Settlement Interval)

p_{ru_c}	$\equiv$	Reg-Ramp-Up capability price
p_{ru_p}	$\equiv$	Reg-Ramp-Up performance price
p_{rd_c}	$\equiv$	Reg-Ramp-Down capability price
p_{rd_p}	$\equiv$	Reg-Ramp-Down performance price
p_{eu_c}	$\equiv$	Reg-Energy-Up capability price
p_{eu_p}	$\equiv$	Reg-Energy-Up performance price
p_{ed_c}	$\equiv$	Reg-Energy-Down capability price
p_{ed_p}	$\equiv$	Reg-Energy-Down capability price
$S_{ru,j}$	$\equiv$	Reg-Ramp-Up settlement credit for resource ***j***
$S_{rd,j}$	$\equiv$	Reg-Ramp-Down settlement credit for resource ***j***
$S_{eu,j}$	$\equiv$	Reg-Energy-Up settlement credit for resource ***j***
$S_{ed,j}$	$\equiv$	Reg-Energy-Down settlement credit for resource ***j***
m_{ru}	$\equiv$	Reg-Ramp-Up signal mileage
m_{rd}	$\equiv$	Reg-Ramp-Down signal mileage
q_{eu}	$\equiv$	Integral of the absolute value of the Reg-Energy signal
q_{ed}	$\equiv$	Integral of the absolute value of the Reg-Energy signal

Threshold Ramp-Rates and Effective Cleared Quantities

For Reg-Ramp-[Up/Down], and Reg-Energy-[Up/Down], a resource ***j*** must meet a specific threshold ramp-rate or else its Effective Cleared MW Quantity will be scaled down from its Cleared MW Quantity (the threshold ramp rate for Reg-Ramp (e.g. 1 MW/sec) will be much higher than it is for Reg-Energy (e.g. 0.1 MW/sec)):

$$\tilde{Q}_{ru,j} = Q_{ru,j} \frac{min(\alpha_j, \tilde{\alpha}_r)}{\tilde{\alpha}_r} \quad [1]$$

$$\tilde{Q}_{rd,j} = Q_{rd,j} \frac{min(\alpha_j, \tilde{\alpha}_r)}{\tilde{\alpha}_r} \quad [2]$$

$$\tilde{Q}_{eu,j} = Q_{eu,j} \frac{min(\alpha_j, \tilde{\alpha}_e)}{\tilde{\alpha}_e} \quad [3]$$

$$\tilde{Q}_{ed,j} = Q_{ed,j} \frac{min(\alpha_j, \tilde{\alpha}_e)}{\tilde{\alpha}_e} \quad [4]$$

The effective cleared quantities for the PJM system are then

$$\tilde{Q}_{ru} = \sum_{j=1}^{N_{ru}} \tilde{Q}_{ru,j} \quad [5]$$

$$\tilde{Q}_{rd} = \sum_{j=1}^{N_{rd}} \tilde{Q}_{rd,j} \quad [6]$$

$$\tilde{Q}_{eu} = \sum_{j=1}^{N_{eu}} \tilde{Q}_{eu,j} \quad [7]$$

$$\tilde{Q}_{ed} = \sum_{j=1}^{N_{ed}} \tilde{Q}_{ed,j} \quad [8]$$

Where N_{ru}, N_{rd}, N_{eu}, and N_{ed} represent the number of resources that clear the Reg-Ramp-Up, Reg-Ramp-Down, Reg-Energy-Up, and Reg-Energy-down markets respectively.

Ideal Regulation Response

Consider an ideal regulation response which would have the effect of eliminating any frequency deviation at time ***t***. This ideal response can be decomposed into the various regulation signal components, along with a deficiency term $\boldsymbol{\epsilon(t)}$, which may arise due to the bounds on the regulation signals and/or the effective quantities cleared for each regulation product.

$$\tilde{\Psi}(t) = \tilde{Q}_{ru} \cdot \psi_{ru}(t) + \tilde{Q}_{rd} \cdot \psi_{rd}(t) + \tilde{Q}_{eu} \cdot \psi_{eu}(t) + \tilde{Q}_{ed} \cdot \psi_{ed}(t) + \epsilon(t)$$

[9]

In practice, even when $\boldsymbol{\epsilon(t)} = 0$, the ideal regulation response will generally not be achievable due to lag times in communications and finite ramp rates for the resources providing the three products. The actual regulation response will be:

$$\Psi(t) = D_{ru} + D_{rd} + D_{eu} + D_{ed}$$

[10]

The task of the system operator will be to procure enough of the various regulation products and set requirements such that an appropriate measure of the frequency deviations interchange imbalances lie within an allowable tolerance.

Regulation-Ramp-(Up/Down)

The Reg-Ramp-Up and Reg-Ramp-Down products are primarily intended to handle potentially large but short-lived deviations in frequency. For longer-lived deviations in frequency these resources should be relieved by slower ramping resources. Since many of the fastest ramping resources will be energy-limited, it is critical that a degree of neutrality be enforced between the Reg-Ramp-Up signal and the Reg-Ramp-Down signal.

Define the signal bias as:

$$\lambda(t) = \int_{t_k}^{t} \left(\psi_{ru}(t) + \psi_{rd}(t)\right) dt \qquad [11]$$

Where t_k represents the most recent point in time prior to t for which $\lambda(t) = 0$. Define t_{k+1} as the first time after t_k for which $\lambda(t) = 0$. Thus,

$$\int_{t_k}^{t_{k+1}} \left(\psi_{ru}(t) + \psi_{rd}(t)\right) dt = 0 \qquad [12]$$

Such that

$$t_{k+1} - t_k \leq \tau \qquad [13]$$

Where τ is the maximum time allowed for Reg-Ramp neutrality to be achieved, which is assumed here to be 15 minutes. Though it may not always be possible to achieve neutrality within the allowable timeframe, doing so should be a very high priority and failures to do so should be monitored so that adjustments can be made in procurements going forward if necessary.

Reg-Ramp signals will be set to address the regulation response imbalance that results from a lack of convergence of the Reg-Energy dispatch to the ideal regulation response.

$$\Phi(t) = \tilde{\Psi}(t) - D_{eu}(t) - D_{ed}(t) \qquad [14]$$

$$\psi_{ru}(t) = \begin{cases} min\left(\frac{\Phi(t)}{\bar{Q}_{ru}}, 1\right) & \Phi(t) \geq 0 \\ 0 & \Phi(t) < 0 \end{cases} \qquad [15]$$

$$\psi_{rd}(t) = \begin{cases} 0 & \Phi(t) \geq 0 \\ max\left(\frac{\Phi(t)}{\hat{Q}_{rd}}, -1\right) & \Phi(t) < 0 \end{cases} \quad [16]$$

Resolving the regulation response imbalance may take some time because the Reg-Ramp resources will have finite ramp rates but also because there may not be enough effective Reg-Ramp cleared MWs to immediately cover the imbalance.

Regulation-Energy

The Reg-Energy products have two primary purposes:

1) To relieve Reg-Ramp resources from extended pegging
2) To ensure neutrality of the Reg-Ramp signals

At a given point in time, the cumulative bias of the Reg-Ramp signals ***λ(t)*** may be non-zero. Depending on how long it has been since the last time the bias was zero, the amount of time remaining in the current window will vary. Thus, the urgency of neutralizing the signal becomes greater the longer the bias persists. As time approaches the end of the neutrality window, the amount of time remaining to ensure the Reg-Ramp signals are neutral approaches zero and the Reg-Ramp required neutralization rate approaches positive or negative infinity depending on the sign of ***λ(t)*** .

$$\dot{\lambda}(t) = \begin{cases} \frac{\lambda(t)}{\tau - (t - t_k)} & (t - t_k) < \tau \\ \frac{\lambda(t)}{0} & (t - t_k) \geq \tau \end{cases} \quad [17]$$

To help limit this, we can scale the rate in such a way that the target neutralization time is some fraction of the time remaining in the window. The Reg-Energy MW response needed to offset the cumulative Reg-Ramp signal bias over the desired time frame is:

$$\Lambda(t) = \begin{cases} \eta \cdot \dot{\lambda}(t) \cdot \tilde{Q}_{ru} & \lambda(t) > 0 \\ 0 & \lambda(t) = 0 \\ \eta \cdot \dot{\lambda}(t) \cdot \tilde{Q}_{rd} & \lambda(t) < 0 \end{cases} \quad [18]$$

The parameter ***η*** is the Reg-Ramp required neutralization rate scaling factor described above. For example, if ***η*** is equal to 3, then the Reg-Energy signal will attempt to drive the Reg-Ramp signal's current bias to neutrality in one-third of the time remaining in the current neutrality window. However, even with this safeguard, it is possible that in some instances, the Reg-Ramp signals will not be able to achieve a zero bias within the maximum allowed time.

Ideally, to accomplish both objectives stated above, the Reg-Energy-[Up/Down] signal would be set equal to

$$\tilde{\psi}_e(t) = \frac{\tilde{\Psi}(t)}{\tilde{Q}_e} + \frac{\Lambda(t)}{\tilde{Q}_e} \quad [19]$$

With positive values corresponding Reg-Energy-Up and negative values corresponding to Reg-Energy-Down

Since the actual Reg-Energy signals are bounded between [0,1] and [-1,0], the actual Reg-Energy signals will be:

$$\psi_{eu}(t) = \begin{cases} min(\tilde{\psi}_e(t), 1) & \tilde{\psi}_e(t) \geq 0 \\ 0 & \tilde{\psi}_e(t) < 0 \end{cases}$$ [20]

$$\psi_{ed}(t) = \begin{cases} 0 & \tilde{\psi}_e(t) \geq 0 \\ max(\tilde{\psi}_e(t), -1) & \tilde{\psi}_e(t) < 0 \end{cases}$$ [21]

Performance Scores

Performance Scores are intended to penalize resources for not responding to the respective signal in an amount of time deemed appropriate.

Reg-Ramp-Up

$$\delta_{ru,j}(t_i) = \psi_{ru}(t_i) \cdot \tilde{Q}_{ru,j} - D_{ru,j}(t_i)$$ [22]

$$\Delta t_i = t_i - t_{i-1}$$ [23]

$$\Delta D_{ru,j}(t_i) = D_{ru,j}(t_i) - D_{ru,j}(t_{i-1})$$ [24]

$$\nu_{ru,j}(t_i) = \begin{cases} min(\delta_{ru,j}(t_i), \alpha_{\tilde{r}} \cdot \tilde{Q}_{ru,j} \cdot \Delta t_{i+1}) & \delta_{ru,j}(t_i) \geq 0 \\ max(\delta_{ru,j}(t_i), -\alpha_{\tilde{r}} \cdot \tilde{Q}_{ru,j} \cdot \Delta t_{i+1}) & \delta_{ru,j}(t_i) < 0 \end{cases}$$ [25]

$$\gamma_{ru,j}(t_i) = \begin{cases} max(\nu_{ru,j}(t_{i-1}) - \Delta D_{ru,j}(t_i), 0) & \nu_{ru,j}(t_{i-1}) \geq 0 \\ min(\nu_{ru,j}(t_{i-1}) - \Delta D_{ru,j}(t_i), 0) & \nu_{ru,j}(t_{i-1}) < 0 \end{cases}$$ [26]

$$F_{ru,j} = max\left(1 - \frac{\sum_{i=1}^{n} |\gamma_{ru,j}(t_i)|}{\sum_{i=1}^{n} |\nu_{ru,j}(t_i)|}, 0\right)$$ [27]

Though the index ***i*** is summed over the current settlement interval from ***1*** to ***n***, it is defined for values outside of this range. For example, ***i=0*** would correspond to the last signal tick of the previous settlement interval and ***i=n+1*** would correspond to the first signal tick of the following settlement interval.

Reg-Ramp-Down, Reg-Energy-Up, and **Reg-Energy-Down** will have the same formulae as Reg-Ramp-Up except that the subscripts are adjusted accordingly.

Under this formulation, a resource has one signal tick to reach its expected response. If this timeframe is too small to be practical, the response deviation measure could be modified to allow for longer response times. However, resources should never be penalized for having reached their expected response too quickly, especially if the expected response for subsequent signal ticks contradicts the expected response for the original signal tick.

Settlements

Regulation resources will receive a regulation credit for providing a particular regulation product. There will also be times when regulation resources may have an energy settlement which results from net energy suppled to or taken from the grid. Since Regulation generally is not an energy product, and Reg-Ramp-Up and Reg-Ramp-Down are constructed to be neutral on relatively short time frames, it follows that energy settlements should be designed in such a way that a resource supplying equal quantities of Reg-Ramp-Up and Reg-Ramp-Down during a specific settlement interval should have no energy settlement. Reg-Ramp and Reg-Energy resources will each receive a capability payment along with a performance payment. The structure of the performance payment will be different based on the essential service each is providing.

The Reg-Ramp-Up settlement credit for resource ***j*** is:

$$S_{ru,j} = \tilde{Q}_{ru,j} \cdot \left(p_{ru\_c} + p_{ru\_p} \cdot m_{ru}\right) \cdot F_{ru,j} \quad [28]$$

Where $\boldsymbol{p_{ru\_c}}$ is the Reg-Ramp-Up capability price, $\boldsymbol{p_{ru\_p}}$ is the Reg-Ramp-Up performance price, $\boldsymbol{F_{ru,j}}$ is the Reg-Ramp-Up performance score for resource ***j***, and $\boldsymbol{m_{ru}}$ is the Reg-Ramp-Up signal mileage.

$$m_{ru} = \sum_{i=1}^{n} \left|\psi_{ru}(t_i) - \psi_{ru}(t_{i-1})\right| \quad [29]$$

Where ***i*** is an index of discrete signal ticks that span the settlement period.

The Reg-Ramp-Down settlement credit has a similar structure.

$$S_{rd,j} = \tilde{Q}_{rd,j} \cdot \left(p_{rd\_c} + p_{rd\_p} \cdot m_{rd}\right) \cdot F_{rd,j} \quad [30]$$

$$m_{rd} = \sum_{i=1}^{n} \left|\psi_{rd}(t_i) - \psi_{rd}(t_{i-1})\right| \quad [31]$$

For Reg-Energy resources, the performance component is based on the cumulative absolute deviation from load basepoint experienced during the settlement interval.

The Reg-Energy-Up settlement credit for resource ***j*** is:

$$S_{eu,j} = \tilde{Q}_{eu,j} \cdot \left(p_{eu\_c} + p_{eu\_p} \cdot q_{eu}\right) \cdot F_{eu,j} \qquad [32]$$

$$q_{eu} = \int_{t_{s\_0}}^{t_{s\_f}} \psi_{eu}(t)\ dt \qquad [33]$$

The Reg-Energy-Up settlement credit for resource ***j*** is:

$$S_{ed,j} = \tilde{Q}_{ed,j} \cdot \left(p_{ed\_c} + p_{ed\_p} \cdot q_{ed}\right) \cdot F_{ed,j} \qquad [34]$$

$$q_{ed} = -\int_{t_{s\_0}}^{t_{s\_f}} \psi_{ed}(t)\ dt \qquad [35]$$

Where t_{s_0} and t_{s_f} are the start and end times of the settlement interval respectively.

Clearing

TBD