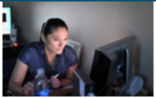
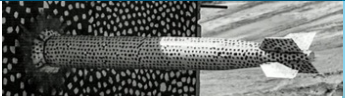
National Laboratories

Primary Frequency Response Reserve Products for Inverter-Based Resources[1]





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Presented by:

Manuel Garcia, Ross Baldick, Felipe Wilches-Bernal

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Inverter-Based Resources & Primary Frequency Response

- Inverter-Based Resources (IBRs) have been detrimental to primary freq. control.
  - Do not provide inertia.
  - Traditionally do not provide frequency control.
- Difficulties in performing primary frequency control.
  - Low inertia makes frequency control more difficult to perform.
  - Accommodating large contingencies is difficult (e.g. nuclear power plant).
- Some regions have proposed new ancillary services for primary frequency control.
  - ERCOT[1], NEM[2], and National Grid[3] proposed new ancillary services for primary frequency control.
  - Western and Eastern interconnect have not proposed such ancillary services.

Table: Yearly minimum inertia levels and largest contingencies in various regions.

ISO/Region	US West[4]	US East[4]	(Texas) ERCOT[4]	(Australia) NEM[5]	(United Kingdom) National Grid[6 and 7]
Yearly Minimum Inertia (GWs)	472	1281	134	4.4	129
Largest Contingency (MW)	2626	4500	2750	100	1260
Inertia/Contingency Ratio (s)	179	284	48	44	102

1 Pengwei Du et al. “New Ancillary Service Market for ERCOT”. In: *IEEE Access* 8 (2020), pp. 178391–178401.

2 Australian Energy Market Operator. *Fast frequency response in the NEM*. Tech. rep. 2017.

3 Lexuan Meng et al. “Fast frequency response from energy storage systems—A review of grid standards, projects and technical issues”. In: *IEEE Transactions on Smart Grid* 11.2 (2019), pp. 1566–1581.

4 North American Electric Reliability Corporation. *Forward Looking Frequency Trends Technical Brief: ERS Framework Measures 1, 2, and 4: Forward Looking Frequency Analysis*. Technical Report, 2018.

5 Australian Energy Market Operator. *Notice of South Australia Inertia Requirements and Shortfall*. Tech. rep. 2020, p. 24.

6 National Grid. *Future Requirements for Balancing Services*. Tech. rep. National Grid, 2016, p. 29. URL: https://www.nationalgrid.com.

7 National Grid ESO Data Portal. *System Inertia Data*. Tech. rep. 2020-2021, p. 29. URL: https://data.nationalgrideso.com/system/system-inertia.

New Ancillary Service Market Products

Proposed Ancillary Service Products for Primary Frequency Control

- Proposed in the real-time market (No horizon considered).
  - Various reserve types with different deployment responses.
  - Reserve payments and inertia payments priced at the margin.
- Contribute to primary frequency control.
  - Contribute to arresting frequency decline in response to a large generator outage.
  - Defined only in the upward direction (Consistent with most contingency reserves).
- Synchronous Generators: Two proposed ancillary service products.
  1. Primary Frequency Response (PFR) reserve: Droop control (Similar to ERCOT[1]).
  2. Synchronous Inertia: Automatically provided if committed.
- Inverter-based Resources (IBR): Two proposed ancillary service products.
  1. Fast Frequency Response (FFR) Reserve: Step response (Similar to ERCOT[1]).
  2. Virtual Inertia (VI) Reserve: Mimics synchronous inertia.

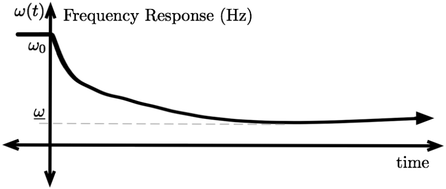
[1] Pengwei Du et al. "New Ancillary Service Market for ERCOT". In: *IEEE Access* 8 (2020), pp. 178391–178401.

Proposed Models for Ancillary Service Products

Inertia and Frequency Dynamics

Simple Swing Equation neglects damping.
System frequency is $\omega(t)$, nominal frequency is ω_0, inertia from generator i is M_i, net-demand is $e(t)$.

$$\frac{d\omega(t)}{dt} = \frac{\omega_0}{2(1^\dagger M)}(1^\dagger m(t) + 1^\dagger p(t) + 1^\dagger d(t) - e(t)).$$

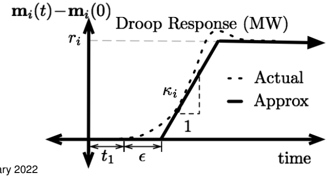


PFR Reserve r

(Droop Control)

$m_i(t)$: Ramp in mech. power
r_i: PFR reserve for generator i

Ramp begins after time delay $t_1 + \epsilon$.

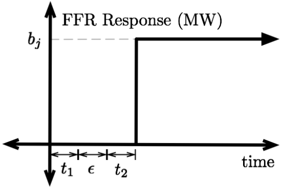


FFR Reserve b

(Step Response)

$d_j(t)$: Instantaneous jump in power
b_j: FFR reserve for IBR j

Response triggered at frequency ω_2.



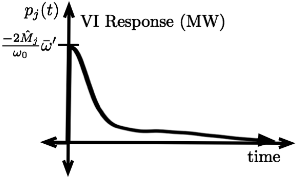
VI Reserve ν

(Virtual Inertia)

$p_i(t)$: derivative of freq.

$\nu_j = \frac{2\hat{M}_j}{\omega_0}\overline{\omega}'$: VI reserve for IBR j

$$p_j(t) = \begin{cases} \frac{-2\hat{M}_j}{\omega_0}\frac{d\omega(t)}{dt} & \omega(t) \leq \omega_0 \\ 0 & \omega(t) > \omega_0 \end{cases}$$



Conventional Generator Model

Products Provided by Generator i

Receives payment for three products.

- G_i: Generation (MW)
- r_i: PFR reserve (MW)
- M_i: Inertia (MWs)

Generator Profit Maximization

Inertia considered fixed in real-time market.
Maximizes payments minus costs.
Subject to physical constraints.

$$\max_{r_i \in \mathbb{R}_+, G_i \in \mathbb{R}_+} \quad \pi_i G_i + \chi r_i + \Psi M_i - C_i(G_i, r_i) \tag{1}$$

$$\underline{G}_i \leq G_i \leq \overline{G}_i - r_i \tag{1a}$$

$$r_i \leq \bar{r}_i \tag{1b}$$

Prices

PFR and inertia prices are uniform for all generators.
Generation price (LMP) is location specific.

- $\text{LMP}_i = \pi_i \ \ \forall i \in [1, \ldots, n]$ (\$/MW)
- PFR Price $= \chi$ (\$/MW)
- Inertia Price $= \Psi$ (\$/MWs)

Constraint Description

(1a): Upper and lower generation limits.

(1b): PFR reserve limit $\bar{r}_i$.

- Fixed from generator's perspective.
- Chosen by the ISO.

Inverter-Based Resource (IBR) Model

Products Provided by IBR j

Receives payment for three products.

- f_j: Electric Generation (MW)
- b_j: FFR reserve (MW)
- ν_j: VI reserve (MW)

IBR Profit Maximization

Maximizes payments minus costs.
Subject to physical constraints.

$$\max_{\substack{f_j \in \mathbb{R}, \nu_j \in \mathbb{R}_+ \\ b_j \in \mathbb{R}_+}} \pi^\dagger H_j f_j + \phi b_j + \psi \nu_j - P_j(f_j, b_j, \nu_j) \quad (2)$$

$$\underline{b}_j \leq f_j \leq \overline{b}_j - b_j - \nu_j \quad (2a)$$

$$\underline{B}_j \leq \tau f_j \leq \overline{B}_j - \Delta t b_j - \frac{(\omega_0 - \omega)}{\overline{\omega}'} \nu_j \quad (2b)$$

Prices

FFR and VI prices are uniform for all IBRs.
Generation price (LMP) is location specific.

- $\text{LMP}_j = \pi^\dagger H_j \ \ \forall j \in [1, \ldots, \beta]$ (\$/MW)
- FFR Price $= \phi$ (\$/MW)
- VI Price $= \psi$ (\$/MW)

Constraint Description

(2a): Power generation limits.

(2b): Energy generation limits.

- FFR reserve must be capable of deployment for time Δt.
- Real-time market interval length is τ.
- VI energy requirement $\frac{(\omega_0 - \omega)}{\overline{\omega}'} \nu_j$ derived from VI signal.

Primary Frequency Response Reserve Requirements

Defining Adequate Primary Frequency Response

- Accommodates largest contingency (Often the sum of the 2 largest generators[1]).
- Maintain frequency above threshold at which firm load is shed.

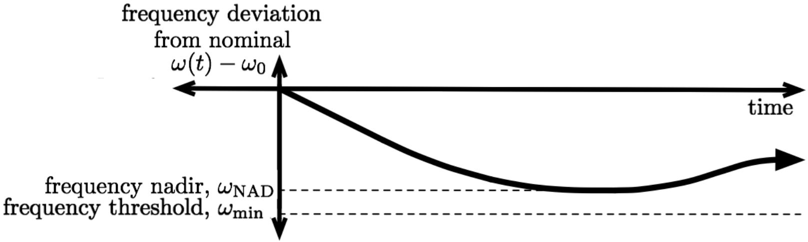


Figure: Frequency response to outage of the 2 largest generators.

[1] ERCOT. *NPRR 863: Creation of Primary Frequency Response Service Product and Revisions to Responsive Reserve.* Tech. rep. ERCOT, 2018.

Extending Reserve Requirements from Previous Work[1] and[2]

Overall Requirement
(Linear constraint)

$$\mathbf{1}^\dagger r + \mathbf{1}^\dagger b \geq L$$

Intuition

$h(\mathbf{1}^\dagger M, \mathbf{1}^\dagger b)$ represents the time by which all PFR must be deployed.

Limit decreases with decreasing:

- inertia $\mathbf{1}^\dagger M$
- FFR reserve $\mathbf{1}^\dagger b$
- ramp rate κ_i

From simulation ramp rates κ_i vary from 1MW/s to 20MW/s.

Rate-Based PFR Limit
(Non-convex constraint)

$$r_i \leq \kappa_i h(\mathbf{1}^\dagger M, \mathbf{1}^\dagger b) \quad \forall i \in [1, \ldots, n]$$

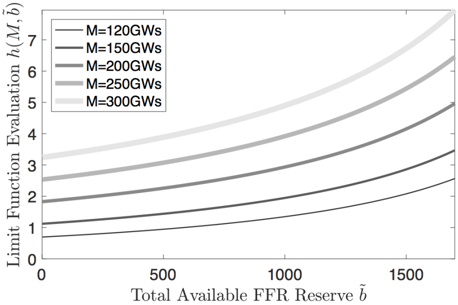


Figure: Function $h(M, \tilde{b})$ with ERCOT parameters, where $\tilde{b}$ represents the total FFR reserve $\mathbf{1}^\dagger b$.

[1] Manuel Garcia and Ross Baldick. "Real-time co-optimization: Interdependent reserve types for primary frequency response". In: *Proceedings of the Tenth ACM International Conference on Future Energy Systems*. 2019, pp. 550–555.

[2] Manuel Garcia and Ross Baldick. "Requirements for Interdependent Reserve Types Providing Primary Frequency Control". In: *IEEE Transactions on Power Systems* (2021).

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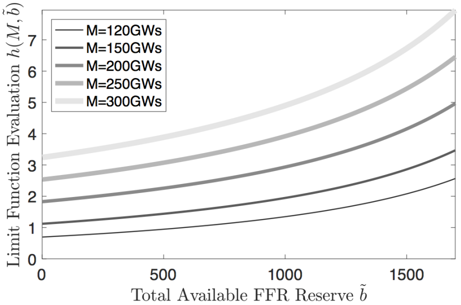
- ramp rate κ_i

From simulation ramp rates κ_i vary from 1MW/s to 20MW/s.

Rate-Based PFR Limit

(Non-convex constraint)

$$r_i \leq \kappa_i h(\mathbf{1}^\dagger M + \frac{\omega_0}{2\omega'} \mathbf{1}^\dagger \nu, \mathbf{1}^\dagger b) + \delta \quad \forall i \in [1, \ldots, n]$$



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[2] Manuel Garcia and Ross Baldick. “Requirements for Interdependent Reserve Types Providing Primary Frequency Control”. In: *IEEE Transactions on Power Systems* (2021).

Real-Time Co-Optimization

Constraint Description

- (3a)-(3b) are DC transmission constraints
- (3c)-(3d) are reserve requirements
- (3e)-(3f) are generator private constraints
- (3g)-(3h) are IBR private constraints

Prices

Defined by Lagrange multipliers of (3).
Marginal benefit of procuring additional unit of product.

$$\text{LMP}_i = \quad \pi_i = -\lambda^\star - S_i^\dagger \zeta^\star \quad \forall i \in [1, \ldots, n]$$

$$\text{PFR Price} = \quad \chi = \mu^\star$$

$$\text{FFR Price} = \quad \phi = \mu^\star + \gamma^{\star\dagger} \kappa \nabla_2 h$$

$$\text{VI Price} = \quad \psi = \gamma^{\star\dagger} \kappa \nabla_1 h \frac{\omega_0}{2\varpi'}$$

$$\text{Inertia Price} = \quad \Psi = \frac{2\varpi'}{\omega_0} \psi$$

Real-Time Co-Optimization

Minimizes total costs subject to constraints.
Lagrange multipliers shown in brackets on left side.

$$\min_{\substack{f \in \mathbb{R}^\beta, \nu \in \mathbb{R}_+^\beta, b \in \mathbb{R}_+^\beta \\ G \in \mathbb{R}_+^n, r \in \mathbb{R}_+^n, \bar{r} \in \mathbb{R}_+^n}} \sum_{i=1}^{n} C_i(G_i, r_i) + \sum_{j=1}^{\beta} P_j(f_j, b_j, \nu_j) \quad (3)$$

$$[\lambda] \quad 1^\dagger (f + G - D) = 0 \quad \text{(3a)}$$

$$[\zeta] \quad S(Hf + G - D) \leq \overline{F} \quad \text{(3b)}$$

$$[\mu] \quad L \leq 1^\dagger r + 1^\dagger b \quad \text{(3c)}$$

$$[\gamma] \quad \bar{r} \leq \kappa h(1^\dagger M + \frac{\omega_0}{2\varpi'} 1^\dagger \nu, 1^\dagger b) + \delta \quad \text{(3d)}$$

$$[\underline{\rho}, \overline{\rho}] \quad \underline{G} \leq G \leq \overline{G} - r \quad \text{(3e)}$$

$$[\underline{\sigma}, \overline{\sigma}] \quad r \leq \bar{r} \leq \overline{R} \quad \text{(3f)}$$

$$[\underline{\varrho}, \overline{\varrho}] \quad \underline{b} \leq f \leq \overline{b} - b - \nu \quad \text{(3g)}$$

$$[\underline{\varsigma}, \overline{\varsigma}] \quad \underline{B} \leq \tau f \leq \overline{B} - \Delta t b - \frac{(\omega_0 - \underline{\omega})}{\varpi'} \nu \quad \text{(3h)}$$

Incentive Alignment Result

Market Participant Incentives

- Optimal Dispatch also maximizes profits of IBRs and generators.
  - Assumes IBRs and generators are price takers.
  - Assumes $\bar{r}$ is from perspective of generator (fixed by ISO).
  - Assumes the dispatch solves the KKT conditions for the co-optimization problem.
    - We do not assume the dispatch represents a global or even a local minima.

Theorem 1: Incentive Alignment

Assume Real-Time Co-Optimization problem (3) is solved to a KKT point and that the prices are set as in previously stated.

(a) The generation dispatch and reserve quantities $(G_i^\star, r_i^\star)$ solve the generator profit maximization problems (1) for each generator i.

(b) The generation dispatch and reserve quantities $(f_j^\star, b_j^\star, \nu_j^\star)$ solve the IBR profit maximization problems (2) for each IBR j.

Sketch of Proof: The KKT conditions for (3) imply the KKT conditions for (1) and (2). This implies global optimality for (1) and (2) because they are convex. This assumes that $\bar{r}_i$ is constant from the perspective of each generator i.

Texas Test Case

ACTIVSg2000 Test Case[1 and 2]

Test Case Details

- Texas A&M Repository.
- 2000 bus representation of Texas.
  - Steady-state MatPower Data.
  - Dynamic Power World Data.
- 544 generators.
  - 2 Largest: $L = 2750$ MW.
  - PFR generators: 50 largest natural gas.
  - $\kappa_i = 20$MW/s and $\epsilon = 0.5$s.

Increasing the Number of IBR Storage Devices

- Each has 1MW of power capacity $\bar{b}_j$.
- Each has random energy capacity $\bar{B}_j$.
  - Uniform distirbuted between $[100, 1000]$MWs.
- IBRs to not provide generation, e.g. $f_j = 0$.
- Increase number of IBRs from 0 to 1000.

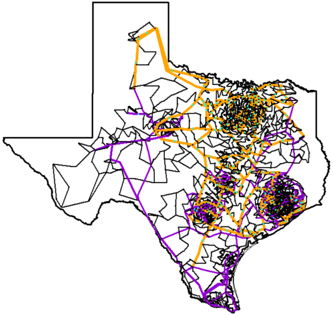


Figure: Test Case Diagram

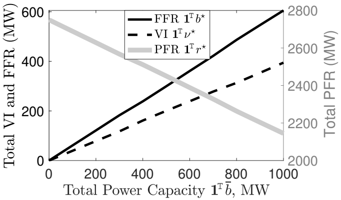
[1] Adam B Birchfield et al. "Grid structural characteristics as validation criteria for synthetic networks". In: *IEEE Transactions on power systems* 32.4 (2017), pp. 3258–3265.

[2] Ti Xu, Adam B Birchfield, and Thomas J Overbye. "Modeling, tuning, and validating system dynamics in synthetic electric grids". In: *IEEE Transactions on Power Systems* 33.6 (2018), pp. 6501–6509.

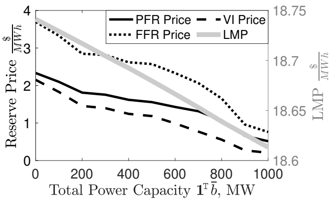
Results: Overall Impact on the System and Market

- Total Reserve Allocation.
  - FFR and VI reserve increase linearly with the number of IBRs.
  - FFR reserve directly replaces PFR reserve.
  - All available power reserve $\mathbf{1}^\dagger \bar{b}$ is used.
- Reserve Prices.
  - Decrease as number of IBRs increase.
  - FFR reserve price is higher than PFR reserve price (similar energy requirements).
  - VI reserve price is lower than FFR reserve price (different energy requirements).
- Total Reserve Payments and Total Savings.
  - Total ancillary service payments reduce from 12329$/h to only 2215$/h.
  - Total generator costs reduce by 1795$/h due to increased PFR reserve limit.

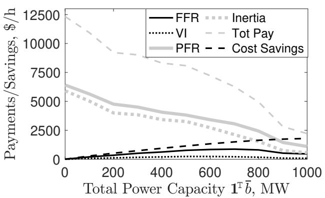
Total Reserve Allocation



Reserve Prices



Total Payments/Costs



Results: Individual IBR Incentives

Energy and Power Capacity Constraints

Constraints for IBR j reduce to:

$$b_j + \nu_j \leq \overline{b}_j \tag{2a}$$

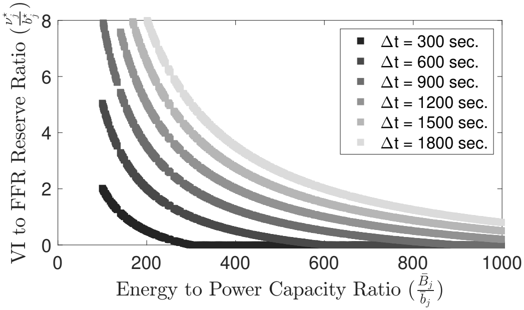
$$\Delta t b_j + \frac{(\omega_0 - \omega)}{\overline{\omega}'} \nu_j \leq \overline{B}_j \tag{2b}$$

Observations

- Both energy and capacity constraints are typically binding.
  - Fully utilize energy and power capacity.
  - Not true if only VI or only FFR reserve.
- Higher power capacity (or lower energy capacity) results in higher VI reserve.
- Higher energy capacity (or lower power capacity) results in higher FFR reserve.

Plot Description

- Time requirement for FFR deployment is Δt.
- Optimal VI to FFR ratio versus energy to power capacity ratio.
- Each curve plots dispatch for 1000 IBRs.
- Curves do not change with number of IBRs.



Conclusions and Future Work

Conclusions

- Proposed PFR reserve, FFR reserve, VI reserve and inertia as products.
- Incentives for generator and IBR market participants.
  - Proposed prices and dispatch align the incenteves of ISO and market participants.
  - IBRs have incentive to fully utilize both energy and power capacities.
    - This is because VI and FFR reserve have significantly different energy and power requirements.
    - Energy constrained IBRs prefer to provide more VI reserve.
    - Power constrained IBRs prefer to provide more FFR reserve.
- Numerical results illustrate that an increasing number of IBRs:
  - decreases total reserve payments and total production costs,
  - increases the PFR reserve limit allowing for a lower cost dispatch, and
  - decreases reserve prices and Locational Marginal Prices.

Future Work

- Implement empirically derived PFR reserve limits in Unit Commitment.
  - Conservative piecewise linear approximation introducing few integer variables.
  - Observe commitment impacts based on inertia.
- Modeling inverter-based storage devices in Unit Commitment problem.
  - Design incentives for storage devices to contribute to ancillary services.
  - Trade-offs between energy requirements and power requirements.
- Constructing rate-based PFR reserve limit from dynamic simulations.

The End

Questions?

Manuel Garcia
(email: mgarc19@sandia.gov)