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Requirements for Interdependent Reserve Types Providing Primary Frequency Control

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Reference
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Inverter-Based Resources & Primary Frequency Response

- Inverter-Based Resources (IBRs) have been detrimental to primary frequency control.
  - Do not provide inertia.
  - Traditionally do not provide frequency control.
- Difficulties in performing primary frequency control.
  - Low system-wide inertia levels makes it more difficult to arrest system-wide frequency decline.
  - Accommodating a large generator trip is difficult.
- 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 1: Yearly minimum inertia levels and largest contingencies in various regions.

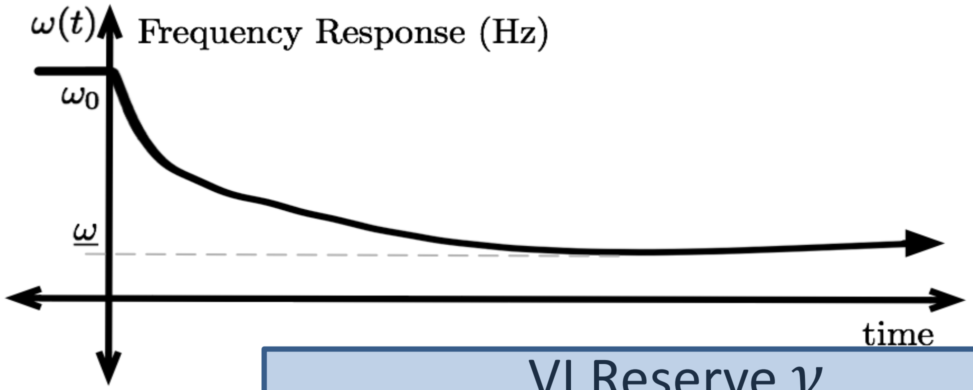
ISO/Region	US West [4]	US East [4]	(Texas) ERCOT [4]	(Australia) NEM [5]	(UK) National Grid [6], [7]
Yearly Minimum Inertia (GWs)	472	1281	134	4.4	129
Largest Contingency (MW)	2626	4500	2750	100	1260
Inertia/Contingency Ratio (s)	179	284	48	44	102

Ancillary Services for Primary Frequency Control

Inertia and the Swing Equation

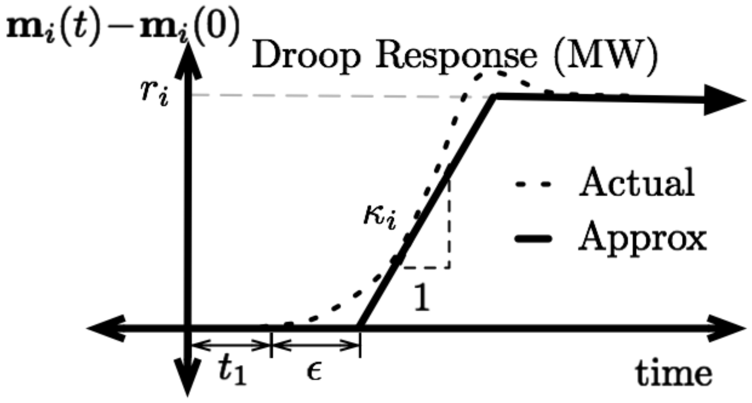
Simple Swing Equation neglects damping.
System frequency is $\omega(t)$, nominal frequency is ω_0, inertia from generator i is M_i, net-demand is $e(t)$.

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



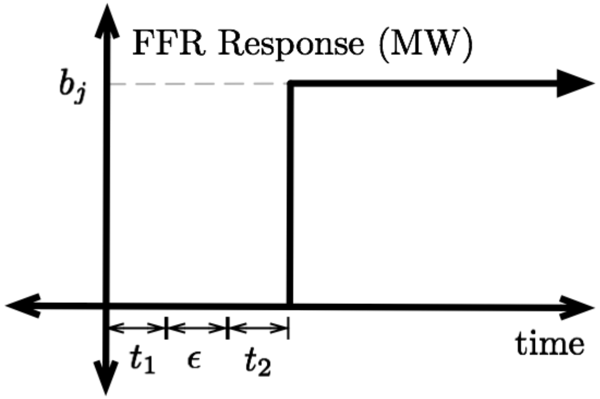
PFR Reserve b

(Droop Control)
$m_i(t)$: Ramp in mechanical power
r_i : PFR reserve for generator i



FFR Reserve b

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

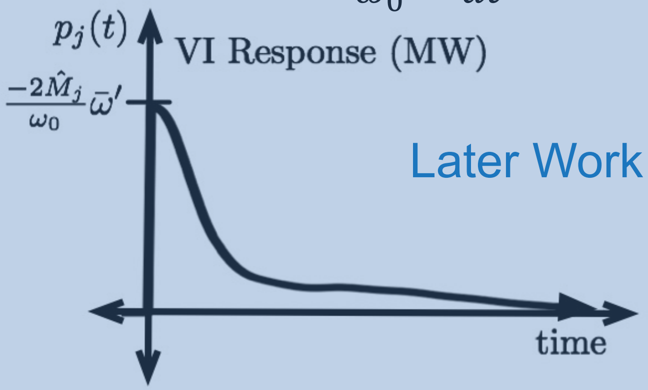


VI Reserve ν

(Virtual Inertia)
$p_j(t)$: Electric power proportional to $\frac{d\omega(t)}{dt}$

$\nu_j(t) = \frac{2\,\hat{M}_j}{\omega_0}\,\bar{\omega}'$: VI reserve for IBR j

$$p_j(t) = \frac{2\,\widehat{M}_j}{\omega_0}\frac{d\omega(t)}{dt}$$



Later Work [8]

ERCOT's Equivalency Ratio Requirement

Equivalency Ratio Requirement

Constraint from [9].

$$1^{\mathrm{T}}R + \alpha(M)1^{T}b \geq \nu(M)$$

Summary

Determined through simulation.
Claims to ensure frequency remains above critical threshold.

Intuition

Places lower bound $\nu(M)$ on total freq. resp. reserve.
FFR reserve is more effective than PFR reserve by a factor of $\alpha(M)$.

Notation

- R: Vector of nominal PFR reserve for generators
- b: Vector of FFR reserve for resources
- M: Total post-outage system inertia
- $\alpha(M)$: Equivalency Ratio
- $\nu(M)$: Requirement Quantity

Important Observation

Often assigns more PFR reserve to generators than they can provide due to ramping limitations.

Makes up for this by over procuring total reserve.

Table 2: Parameters appearing in the equivalency ratio reserve requirement from [9].
The equivalency ratio $\alpha(M)$ and the frequency response reserve requirement $\nu(M)$ are provided for different inertia levels.

Inertia M (GWs)	Equiv. Ratio $\alpha(M)$	Req. Amount $\nu(M)$ (MW)
120	2.2	5200
136	2.0	4700
152	1.5	3750
177	1.4	3370
202	1.3	3100
230	1.25	3040

Inertia M (GWs)	Equiv. Ratio $\alpha(M)$	Req. Amount $\nu(M)$ (MW)
256	1.13	2640
278	1.08	2640
297	1	2240
316	1	2280
332	1	2140
350	1	2140

Proposed Requirement Framework

General Requirement

Sufficient reserve to cover an outage of arbitrary size L.
Intuitive because the requirement quantity is the outage size considered.

$$\mathrm{L} \leq 1^{\mathrm{T}}\mathrm{r} + 1^{\mathrm{T}}b \qquad (1)$$

Assuming all reserve can be delivered before ω_{min} is reached, the frequency will be arrested before ω_{min} is reached.

Notation

- r: Vector of available PFR reserve for generators
- R: Vector o nominal PFR reserve for generators
- b: Vector of FFR reserve for resources
- M: Total post-outage system inertia
- G : Vector of power output for generators
- $\bar{G}$: Vector of generator capacities
- ω_{min}: Minimum frequency threshold

Nominal PFR Reserve R

Head-room required to provide PFR.

$$\mathrm{G} + \mathrm{R} \leq \bar{G} \qquad (2)$$

Available PFR Reserve r

Available before ω_{min} is reached.

$$r \leq R \qquad (3)$$

PFR Reserve Limits

Not all nominal PFR reserve R may be available before ω_{min} is reached.
Limits on available PFR reserve r represent physical ramping limitations,

$$r_i \leq \ell_i(\cdot) \quad \text{for each generator } i \qquad (4)$$

where $\ell_i(\cdot)$ is a limit function that may depend on many system-wide values.

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Proposed PFR Reserve Limits

Empirically Derived PFR Reserve Limits

Equivalency Ratio Requirements

Approximately the same as equivalency ratio requirement from [9]

$$r_i \leq \frac{1}{\alpha(M)} R_i \qquad (5)$$

Empirical PFR reserve limits

Similar method as used to determine equivalency ratios. (In progress)

$$r_i \leq \ell_i(M, 1^T b) \qquad (6)$$

Empirically Derived PFR Reserve Limits

Rate-Based PFR Reserve Limits

Assumes fixed ramp rate κ_i.
Derives $h(\cdot, \cdot)$ from first principles.

$$r_i \leq \kappa_i h(M, 1^T b) \qquad (7)$$

Proportional PFR Reserve Limits

Ramp rate κ_i is proportional to R_i.
Derives $\alpha(M)$ from first principles.

$$r_i \leq \tau_i R_i h(M, 1^T b) \qquad (8)$$

Numerical Results: Texas 2000 Bus Test Case

Texas 2000 Bus Test Case

- PFR generators: 50 largest natural gas
- FFR Reserve Capacity is $\bar{b} = 600MW$.

Figure 2: Total PFR Reserve Allocation

- Rate-based PFR reserve limit assigns exactly enough PFR reserve to cover the contingency L-b=1900 MW.
- Equiv. ratio req. assigns more PFR reserve than necessary.
- Both requirements simultaneously allocates the same total PFR reserve as the equiv. ratio req.

Figure 3: Largest PFR Reserve Allocation

- Equiv. Ratio Req. assigns too much nominal PFR reserve to a single generator.
  - Not all is available before frequency threshold is reached.
- Rate-based PFR reserve limit ensures all PFR reserve is available.
  - Limit increases with inertia
- Enforcing both req. allocates some extra headroom to generators.
  - Disperses PFR reserve among more generators.

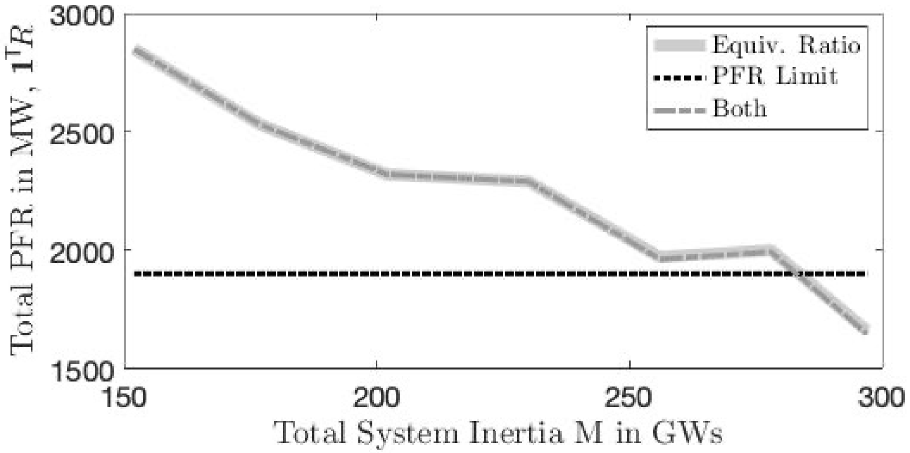

Figure 2:Total PFR reserve in the system as total system inertia varies. [3]

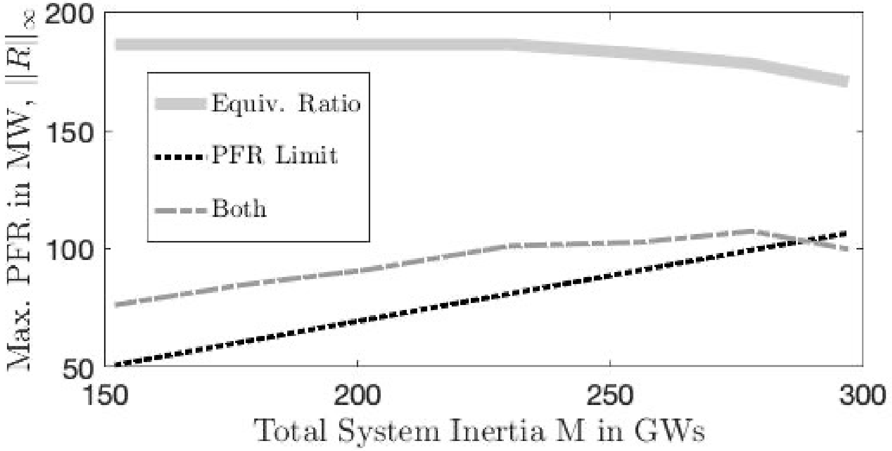

Figure 3: The infinity norm of the PFR reserve vector as total system inertia varies. [3]

Conclusions/Recommendations

- Proposed introduction of new primary frequency response reserve products into wholesale electricity markets.
- Presented ERCOT’s equivalency ratio requirement.
  - Derived equivalency ratios from first principles.
- Proposed more general reserve requirement framework in the form of *PFR reserve limits* to ensure sufficient frequency response.
  - Proposed four different PFR reserve limits.
  - Proposed one PFR Reserve limit that is approximately the same as the equivalency ratio requirement.
- Illustrated the differences between reserve requirements.
  - Rate-based PFR reserve limit spreads out PFR reserve allocation among more generators.
  - Equivalency ratio requirement allocates too much PFR reserve to a single generator and procures more total PFR reserve than is strictly necessary to cover the largest contingency.
  - Both limits can be enforced at the same time, making the requirement more conservative.

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