Cockrell School of Engineering

Real-Time Co-Optimization: Interdependent Reserve Types for Primary Frequency Response

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Outline

1. Motivation and Background
2. Modeling Three Contributors to Arresting Frequency
3. Sufficient Condition for Adequate Reserve Procurement
4. Co-Optimization Problem

Real-Time Co-Optimization in ERCOT

ERCOT Market Changes

1. Introduce real-time co-optimization[1]
   - Security-constrained economic dispatch considers reserve
2. Redefining reserve types providing primary frequency control[2 and 3]
   - Primary Frequency Responsive (PFR) reserve: droop control
     - Response is proportional to frequency deviation
   - Fast Frequency Responsive (FFR) reserve: responds within a few cycles
     - Intended for batteries or load shedding
     - Full and instant response to some frequency threshold violation

[1]ERCOT. *NPRR 863: Creation of Primary Frequency Response Service Product and Revisions to Responsive Reserve*. Tech. rep. ERCOT, Jan. 2018. URL: http://www.ercot.com/mktrules/issues/reports/nprr.
[2]Stephen Reedy. *Simulation of Real-Time Co-Optimization of Energy and Ancillary Services for Operating Year 2017*. Tech. rep. Potomac Economics, June 2018, p. 8. URL: http://www.ercot.com/content/wcm/lists/144930/IMM_Simulation_of_Real-Time_Co-optimization_for_2017.pdf.
[3]ERCOT. *Study of the Operational Improvements and Other Benefits Associated with the Implementation of Real-Time Co-optimization of Energy and Ancillary Services*. Tech. rep. ERCOT, June 2018, p. 10. URL: http://www.ercot.com/content/wcm/lists/144930/Study_of_the_Benefits_of_Real-Time_Co-optimization_FINAL.pdf.

Interaction of Reserve Types

Sufficient Condition for Adequate Reserve Procurement

- Can be included in co-optimization problem
  - Pricing implications for each product
- Condition couples three contributors to arresting frequency
  - 1) Inertia, 2) PFR reserve, and 3) FFR reserve

What is *Adequate Reserve Procurement*?

- System can accommodate simultaneous outage of 2 largest generators[1]
- Maintain frequency above threshold at which firm load is shed[1]

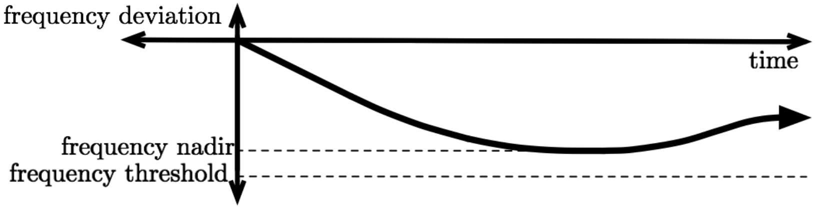

Figure: Frequency requirement in response to 2 largest generator outages

[1]ERCOT 2018a.

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Inertia

Swing Equation

Assume uniform system frequency and simple system dynamics

$$\frac{df(t)}{dt} = \frac{1}{M}(\mathbf{1}^{\dagger} m(t) - e(t)), \tag{1}$$

Notation

$f(t) \in \mathbb{R}$: system frequency
$M \in \mathbb{R}$: system-wide inertia
$e(t) \in \mathbb{R}$: electrical power demand
$m(t) \in \mathbb{R}^n$: mechanical power input from turbine governors
n: number of generators
$\mathbf{1}$: vector of ones

Primary Frequency Responsive (PFR) Reserve

Governor Response (Droop Response) to Large Outage[4]

Ramp in mechanical power supply $m_i(t)$
Intended to conservatively approximate droop control

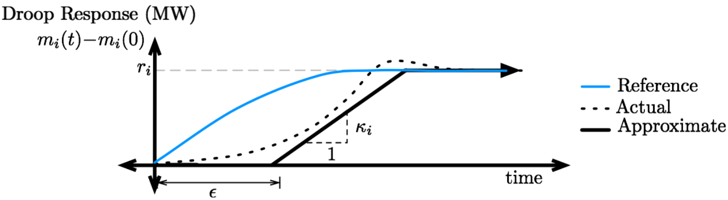


Figure: Turbine governor response to generator outage.

Notation

$f_1 \in \mathbb{R}$: lower frequency dead-band threshold ($f_1 = 59.9833$ Hz)[1]
$\epsilon \in \mathbb{R}$: time delay after reaching dead-band
$\kappa_i \in \mathbb{R}$: constant ramp rate for generator i
$r_i \in \mathbb{R}$: PFR reserve quantity for generator i

[1]ERCOT 2018a.
[4]Héctor Chávez, Ross Baldick, and Sandip Sharma. Governor rate-constrained OPF for primary frequency control adequacy. In: *IEEE Transactions on Power Systems* 29.3 (2014), pp. 1473–1480.

Fast Frequency Responsive (FFR) Reserve

Battery Response (or Load-Shedding) to a Large Outage

Instantaneous jump in electrical power demand $e(t)$
Deploys all available reserve b

- Larger frequency dead-band $f_2 < f_1$
- Neglect any delay in response after reaching dead-band
- Neglect time taken to fully deploy reserve b_j
  - Must fully deploy within 0.5s in ERCOT[5]

Notation

$f_2 \in \mathbb{R}$: lower frequency dead-band threshold ($f_2 = 59.8$ Hz)
$b_j \in \mathbb{R}$: FFR reserve quantity for battery j

[5]Cong Liu and Pengwei Du. Participation of load resources in day-ahead market to provide primary-frequency response reserve. In: *IEEE Transactions on Power Systems* 33.5 (2018), pp. 5041–5051.

System-Wide Frequency Response Model

Plot Description

Top plot: Power imbalance

Bottom plot: Freq. resp.

Swing Eqn.: $\frac{df(t)}{dt} = \frac{1}{M}(\mathbf{1}^{\dagger}m(t) - e(t))$

Sequence of Events

- Generator outage of size L
  - ERCOT: L=2750MW (2 largest generators)
- Frequency hits PFR dead-band f_1
  - ERCOT: $f_1 = 59.9833$Hz (Droop Deadband)
- PFR ramp begins after delay ϵ
  - Assume constant ramp rate K until power balance is met

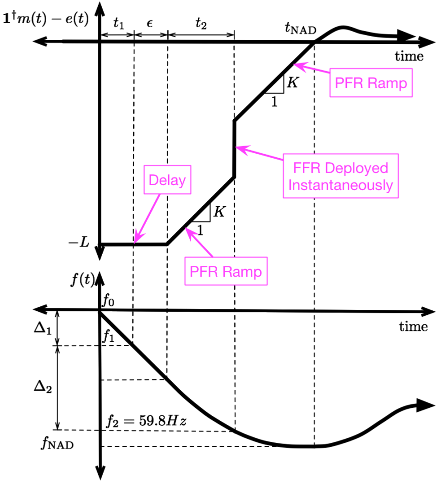


Figure: Plot is not drawn to scale.

System-Wide Frequency Response Model

Plot Description

Top plot: Power imbalance

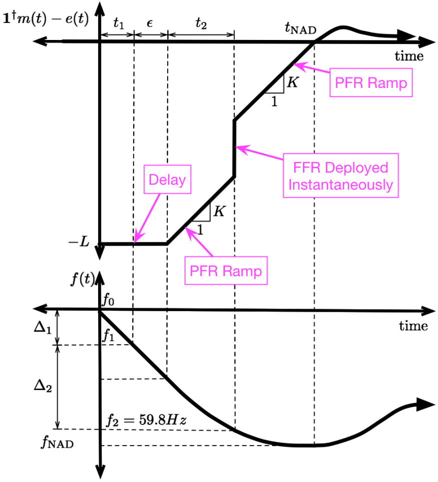
Bottom plot: Freq. resp.

Swing Eqn.: $\frac{df(t)}{dt} = \frac{1}{M}(\mathbf{1}^\dagger m(t) - e(t))$

Continued Sequence of Events

⋮

- Frequency hits FFR dead-band f_2
  - ERCOT: $f_2 = 59.8$ Hz
- FFR deployed instananeously
  - Total FFR reserve denoted $\mathbf{1}^\dagger b$
- PFR ramp continues
- Power is balanced before f_{min}
  - ERCOT: $f_{\text{min}} = 59.4$ Hz



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Frequency Response Assumptions

FFR is Deployed During PFR Ramp

Does not depend on reserve allocation

$\frac{\epsilon L}{M} \leq \Delta_2$ and $\Delta_1 + \Delta_2 \leq f_0 - f_{\text{NAD}}$ (2)

Sufficient Reserve to Restore Power Balance

Constraint in Co-optimization

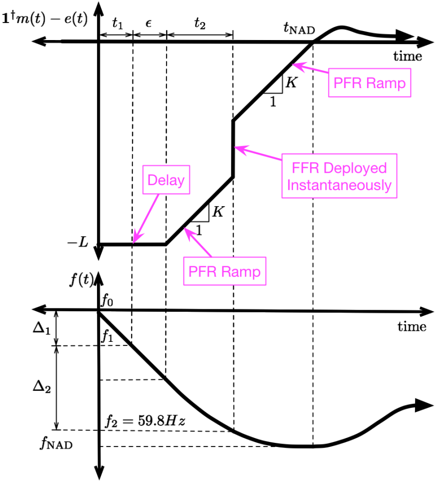
$$\mathbf{1}^\dagger b + \mathbf{1}^\dagger r \geq L \quad (3)$$

No FFR Deployment Overshoot

(FFR does not overshoot the origin in the energy imbalance curve.)

Constraint in co-optimization

$$Kt_2 + \mathbf{1}^\dagger b \leq L \quad (4)$$



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Sufficient Condition for Satisfying Frequency Threshold

Proposition 2 (Sufficient Condition for Adequate Reserve)

Under assumptions (2), (3), and (4),
the frequency nadir satisfies the frequency threshold $f_{\text{NAD}} \geq f_{\text{min}}$
if the following holds:

$$r_i \leq \kappa_i h(M, 1^{\dagger} b) \;\; \forall i \in [1, \dots, n] \tag{5}$$

where the limit function $h(M, \tilde{b})$ is as follows:

$$h(M,\tilde{b}) := \frac{2M(\Delta_2+\Delta_3-\frac{1}{M}\epsilon L)^2(L-\tilde{b})}{\left(\tilde{b}\sqrt{\Delta_3}-\sqrt{(\Delta_2+\Delta_3-\frac{1}{M}\epsilon L)L^2-(\Delta_2-\frac{1}{M}\epsilon L)\tilde{b}^2}\right)^2} \tag{6}$$

Proof: Omitted

Notation Reminder

$r_i \in \mathbb{R}$: PFR reserve quantity for generator i
$b_j \in \mathbb{R}$: FFR Reserve for battery j
$M \in \mathbb{R}$: system inertia
$\kappa_i \in \mathbb{R}$: constant ramp rate for generator i

Rate-Based Reserve Requirement

Rate-Based PFR Limit

(Non-convex constraint)

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

Definition of limit function

$$h(M,\tilde{b}) := \frac{2M(\Delta_2+\Delta_3-\frac{1}{M}\epsilon L)^2(L-\tilde{b})}{\left(\tilde{b}\sqrt{\Delta_3}-\sqrt{(\Delta_2+\Delta_3-\frac{1}{M}\epsilon L)L^2-(\Delta_2-\frac{1}{M}\epsilon L)\tilde{b}^2}\right)^2}$$

The limit increases with:

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

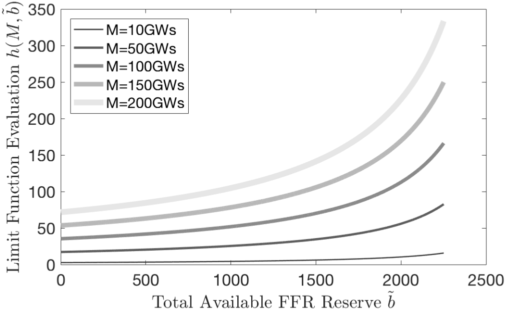

Figure: Function $h(M,\tilde{b})$ with ERCOT parameters.

Outline

Co-Optimization with Reserve Sufficiency Condition

Summary

Real-time market

FFR represents batteries

Reserve costs are included

Constraints

(7a): Power Balance

(7b): Line Limits

(7c): PFR headroom

(7d): PFR Offer

(7e): FFR Offer

(7f): Assumption (3)

(7g): Sufficient condition (5)

$$\min_{b\in\mathbb{R}^n_+, p\in\mathbb{R}^n_+, r\in\mathbb{R}^n_+} \quad c(p)+c_1(r)+c_2(b) \tag{7}$$

$$st: \mathbf{1}^\dagger(p-d)=0 \tag{7a}$$

$$H(p-d)\leq \bar{T} \tag{7b}$$

$$p+r\leq \bar{p} \tag{7c}$$

$$r\leq \bar{r} \tag{7d}$$

$$b\leq \bar{b} \tag{7e}$$

$$L\leq 1^\dagger r+1^\dagger b \tag{7f}$$

$$r_i\leq \kappa_i h(M,1^\dagger b)\ \ \forall i\in[1,n] \tag{7g}$$

Omitted Constraint

Assumption (4) is omitted, inherently assume little offered FFR

Co-Optimization with Reserve Sufficiency Condition

Summary

Real-time market

FFR represents batteries

Reserve costs are included

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(7a): Power Balance

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$$\min_{b \in \mathbb{R}^n_+, p \in \mathbb{R}^n_+, r \in \mathbb{R}^n_+} \quad c(p) + c_1(r) + c_2(b) \tag{7}$$

$$st: \mathbf{1}^\dagger (p - d) = 0 \tag{7a}$$

$$H(p - d) \leq \bar{T} \tag{7b}$$

$$p + r \leq \bar{p} \tag{7c}$$

$$r \leq \bar{r} \tag{7d}$$

$$b \leq \bar{b} \tag{7e}$$

$$L \leq 1^\dagger r + 1^\dagger b \tag{7f}$$

$$r_i \leq \kappa_i h(M, 1^\dagger b) \;\; \forall i \in [1, n] \tag{7g}$$

Omitted Constraint

Assumption (4) is omitted, inherently assume little offered FFR

Conclusions and Future Work

Conclusions

- Presented a reserve requirement that accounts for
  - turbine governor ramping ability
  - total system inertia
  - coupling between FFR reserve and PFR reserve
- Rate-based PFR reserve limit is inherently non-linear

Future Work

- Interaction with the 20% HSL limit.
  - Should the 20% HSL limit be tightened?
- Interaction with Operating Reserve Demand Curves (ORDCs)
- Obtain accurate dynamic models to determine ramp rates κ_i
- Approximating rate-based PFR reserve limit
  - linear approximations
  - Piecewise linear approximation with integer variables

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