Ancillary Services

Quantitative Energy Economics

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Ancillary Services

Ancillary services: services necessary to support the transmission of electric power from seller to purchaser given the obligations of control areas to maintain reliable operations

1. Scheduling and dispatch
2. Primary reserve
3. Secondary and tertiary reserve
4. Energy imbalance
5. Real power loss replacement
6. Voltage control
7. Others (black start capability, power quality)

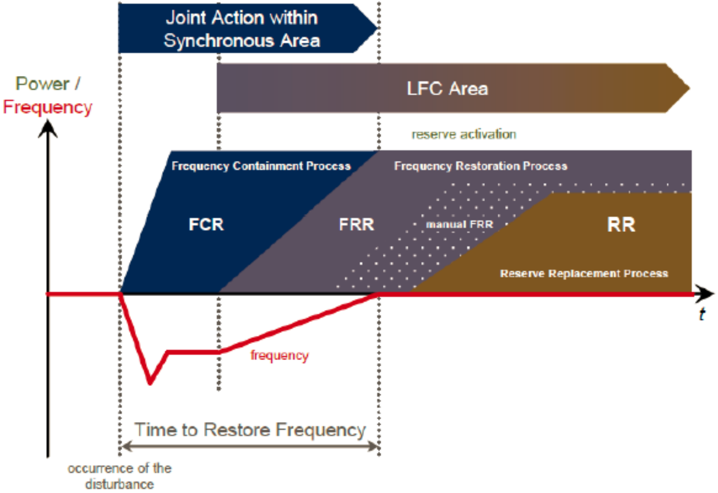
Table of Contents

Uncertainty

- Continuous uncertainty: renewable energy and load forecast errors
- Discrete uncertainty/ contingencies: Outages of system components (transformers, transmission lines, generators, large loads)

Frequency Control and Restoration

System frequency is an indicator of supply-demand balance



Primary Reserve

Primary reserve (a.k.a. primary control, frequency containment reserve) is the first line of defense

1. Change of inertia in generator rotors: immediate
2. Frequency-responsive governors (automatic controllers): reaction is immediate, may take a few seconds reach target
3. Automatic generation control (AGC, a.k.a. load frequency control, regulation): updated once every few seconds up to a minute

Secondary Reserve

Secondary reserve (a.k.a. automatic frequency restoration reserve, frequency responsive reserve, secondary control, operating reserve): second line of defense

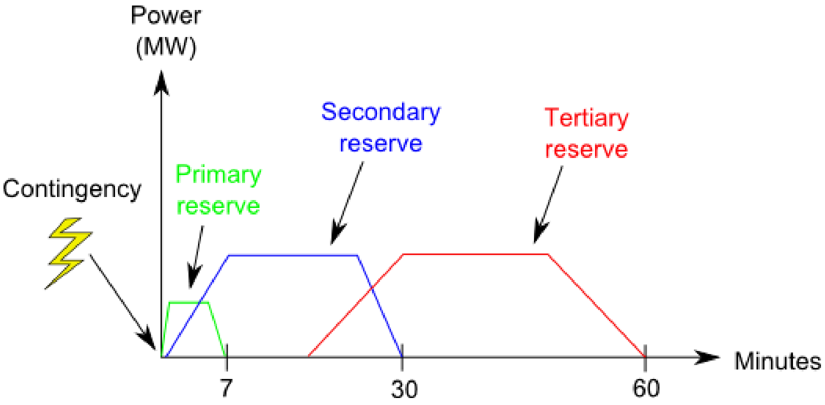
- Reaction in a few seconds, full response within 5-10 minutes
- Classified between spinning and non-spinning reserve
  - **Spinning reserve**: generators that are on-line
  - **Non-spinning reserve**: generators that are off-line but can start rapidly (or imports)
- Requirements dictated by capacity of greatest generator in the system and peak load

Tertiary Reserve

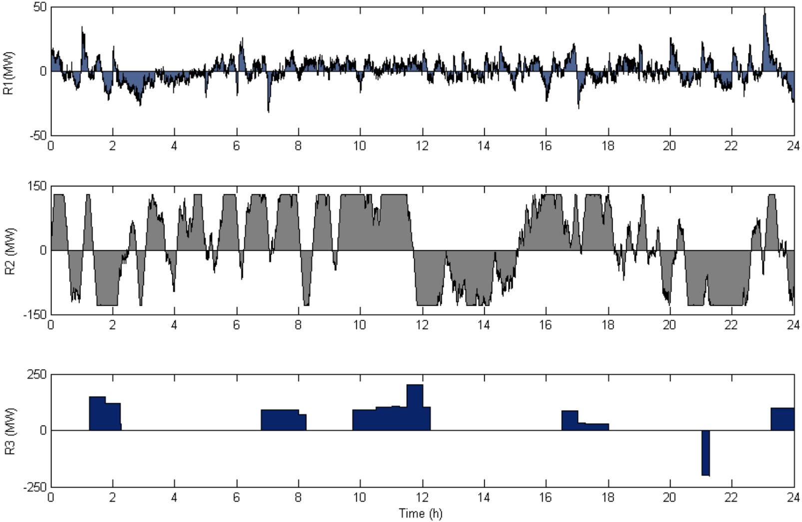
Tertiary reserve (a.k.a. manual frequency restoration services, tertiary control, tertiary reserve, replacement reserve): third line of defense

- Available within 15 minutes

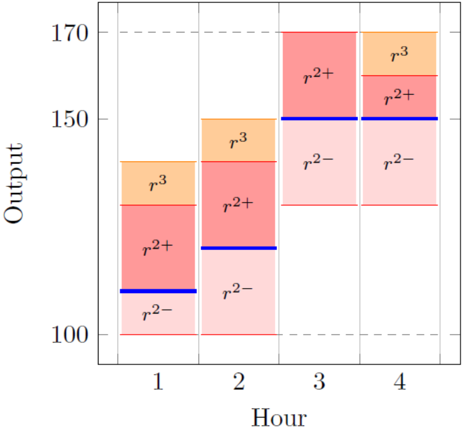
Sequential Activation of Reserves



Reserves in Belgium



Example: Secondary/Tertiary Reserve

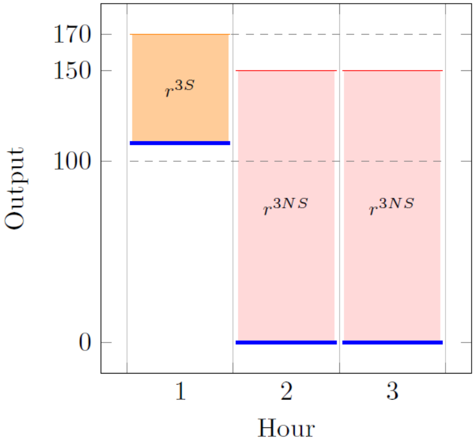


Suppose:

- Upward/downward secondary reserve limit: 20 MW
- Tertiary reserve limit: 10 MW
- Min capacity: 100 MW
- Max capacity: 170 MW
- Planned production: 110 MW (hour 1), 120 MW (hour 2), 150 MW (hour 3), 150 MW (hour 4)

- How much downward secondary?
- How much upward secondary in hours 1-2? hours 3-4?
- How much tertiary in hours 1-2? hours 3-4?

Example: Spin/Non-Spin



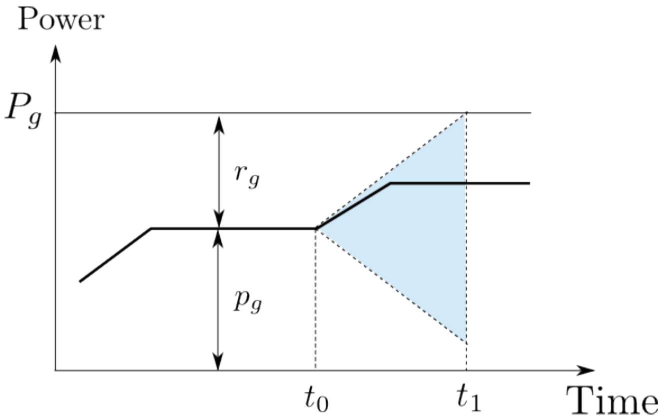
Suppose:

- Non-spin reserve limit: 150 MW
- Min capacity: 100 MW
- Max capacity: 170 MW
- Planned production: 110 MW (hour 1), 0 MW (hour 2), 0 MW (hour 3)

How much spinning reserve in hour 1? non-spinning reserve in hours 2-3?

Table of Contents

Modeling Reserve Constraints



Blue indicates ramp rate, r_g can be offered as reserve at t_0 if response time is at least $t_1 - t_0$

Factors that limit amount of available reserve r_g:

- Generator capacity P_g

$$p_g + r_g \leq P_g$$

- Generator ramp rate R_g

$$r_g \leq R_g$$

Note: R_g depends on *type* (primary, secondary, tertiary) of offered reserve

Denote R as total reserve requirement:

$$\sum_{g \in G} r_g \geq R$$

Co-Optimization of Energy and Reserves

Assume:

- no transmission constraints
- single type of reserve

$$
\begin{aligned}
(EDR): \quad & \max \sum_{l \in L} \int_0^{d_l} MB_l(x)dx - \sum_{g \in G} \int_0^{p_g} MC_g(x)dx \\
(\lambda): \quad & \sum_{l \in L} d_l - \sum_{g \in G} p_g = 0 \\
(\mu): \quad & R \leq \sum_{g \in G} r_g \\
& r_g \leq R_g \\
& p_g + r_g \leq P_g \\
& p_g, d_l, r_g \geq 0
\end{aligned}
$$

Example

- Three generators
  - $P_1 = 100$ MW, $R_1 = 1$ MW/minute, $MC_1 = 10$ \$/MWh
  - $P_2 = 100$ MW, $R_2 = 5$ MW/minute, $MC_2 = 80$ \$/MWh
  - $P_3 = 100$ MW, $R_1 = \infty$, $MC_3 = 0$ \$/MWh
- Inelastic demand $D = 100$ MW
- Secondary reserve (10 minutes) $R = 100$ MW (why 100?)

Optimal solution: use most expensive generators for providing reserve

Solve for reserve first, in order of decreasing marginal cost:

- $r_2 = 50$ MW
- $r_1 = 10$ MW
- $r_3 = 40$ MW

Then, solve for energy, in order of increasing marginal cost:

- $p_3 = 60$ MW
- $p_1 = 40$ MW
- $p_2 = 0$ MW

Additional Features

Notation

- $R1^+$, $R1^-$: primary reserve up and down requirement
- $R2$, $R3$: secondary, tertiary reserve requirement
- $r1^+_{g,1}, r1^+_{g,2}, r1^+_{g,3}$: primary reserve capacity allocated to primary, secondary, tertiary reserve requirements
- $r1^-_g \geq 0$: amount of downwards primary reserve capacity
- $r2_{g,2}, r2_{g,3}$: amount of secondary reserve capacity allocated towards secondary and tertiary reserve requirements
- $r3_g$: amount of tertiary reserve capacity allocated towards tertiary reserve requirements
- $R1_g$, $R2_g$, $R3_g$: amount of primary, secondary, tertiary reserve that can be offered by a generator

- Secondary and tertiary reserve requires upwards capacity only, primary reserve can be upwards and *downwards*[1]

$$\sum_{g \in G} r1^+_{g,1} \geq R1^+, \sum_{g \in G} r1^-_g \geq R1^-$$

$$p_g + \sum_{i=1}^{3} r1^+_{g,i} + \sum_{i=2}^{3} r2_{g,i} + r3_g \leq P_g, p_g - r1^-_g \geq 0$$

- Substitutability: primary reserve $\succ$ secondary reserve $\succ$ tertiary reserve

$$\sum_{g \in G} (r1^+_{g,2} + r2_{g,2}) \geq R2, \sum_{g \in G} (r1^+_{g,3} + r2_{g,3} + r3_g) \geq R3$$

$$\sum_{i=1}^{3} r1^+_{g,i} \leq R1_g, r1^-_g \leq R1_g, \sum_{i=2}^{3} r2_{g,i} \leq R2_g, r3_g \leq R3_g$$

---

[1] Secondary reserve also sometimes distinguished between upwards and downwards

Security Constrained Economic Dispatch (SCED)

SCED: two-stage model that determines secondary reserve by representing contingencies *within* the model

- ω: contingency
- p_g: first-stage decisions
- $p_g(\omega)$: second-stage decisions
- Constraint linking first and second stage:

$$-R_g \leq p_g - p_g(\omega) \leq R_g$$

$$
\begin{aligned}
(SCED): \quad & \min \sum_{g \in G} \int_0^{p_g} MC_g(x)dx \\
& p_g \leq P_g, \sum_{g \in G} p_g = D \\
& p_g(\omega) \leq P_g \cdot 1_g(\omega), \sum_{g \in G} p_g(\omega) = D \\
& -R_g \leq p_g - p_g(\omega) \leq R_g, \text{ if } 1_g(\omega) = 1 \\
& p_g, p_g(\omega) \geq 0
\end{aligned}
$$

Note:

- Inelastic demand, *not* a decision $\Rightarrow$ all demand must be satisfied for all ω
- Objective function: cost of the base case (no contingencies)

- D: system demand
- If $1_g(\omega) = 0$ then generator g is not available in contingency ω
- $N - 1$ **security**: being able to serve demand with $N - 1$ components (i.e. outage of one component)
- $N - k$ **security**: being able to serve demand with $N - k$ components (i.e. outage of k components)

How do we model $N - 1$ security criterion using (*SCED*)?

Which model is easier to solve, (*EDR*) or (*SCED*)?

Example

- Three generators
  - $P_1 = 100$ MW, $R_1 = 1$ MW/minute, $MC_1 = 10$ \$/MWh
  - $P_2 = 100$ MW, $R_2 = 5$ MW/minute, $MC_2 = 80$ \$/MWh
  - $P_3 = 100$ MW, $R_1 = \infty$, $MC_3 = 0$ \$/MWh
- Inelastic demand $D = 100$ MW

(*SCED*) solution identical to (*EDR*) solution: $p_1 = 40$ MW, $p_3 = 60$ MW

... but solutions could differ if (*EDR*) had different R

What is the response when generator 2 is unavailable?

Import Constraints

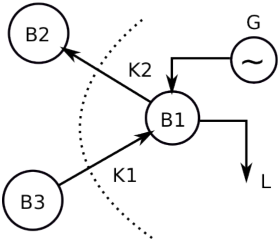
Import constraints limit total power flow on sensitive groups of lines

$$\sum_{k \in IG_j} \gamma_{jk} f_k \quad \leq \quad IC_j, j \in IG$$

- IG: set of import groups
- γ_{jk}: reference direction
- IG_j: set of lines in import group j
- IC_j: flow limit over import group
- f_k: flow on line k

Protection against outages

Bubble Constraints



Logic: if generator G within load pocket $B1$ fails, power needs to come from outside

$$f_{K_1} - f_{K_2} \leq 100$$

- $IG = \{IG_1\}$
- $IC_{IG_1} = 100$ MW
- $\gamma_{IG_1,K_1} = 1$, $\gamma_{IG_1,K_2} = -1$

Table of Contents

Coordination constraints of (EDR):

- Supply equals demand:

$$\sum_{l \in L} d_l - \sum_{g \in G} p_g = 0$$

- Reserve requirement:

$$R \leq \sum_{g \in G} r_g$$

Simultaneous auction for energy and reserves:

- Suppliers submit *ramp rates* and increasing bids. Buyers submit decreasing bids.
- Market operator solves (*EDR*) and announces λ as market clearing price for power, μ as market clearing price for reserve.

- Note: generators submit ramp rates as part of bid
- Power bought by loads from generators
- Reserve bought by market operator from generators

Example

- Three generators
  - $P_1 = 100$ MW, $R_1 = 1$ MW/minute, $MC_1 = 10$ \$/MWh
  - $P_2 = 100$ MW, $R_2 = 5$ MW/minute, $MC_2 = 80$ \$/MWh
  - $P_3 = 100$ MW, $R_1 = \infty$, $MC_3 = 0$ \$/MWh
- Inelastic demand $D = 100$ MW
- Secondary reserve (10 minutes) $R = 100$ MW

Prices:

- Power: $\lambda^\star = 10$ \$/MWh
- Reserve: $\mu^\star = 10$ \$/MWh

Transfers:

- Buyers pay sellers 1000 \$/h for power
- Market operator pays sellers 1000 \$/h for reserve

- Generator 1
  - Reserve earns profit of 10 $/MWh, power earns zero profit
  - Profit maximizing reserve: 10 MW
  - Profit maximizing power: indifferent
- Generator 2
  - Reserve earns profit of 10 $/MWh, power earns profit of -70 $/MWh
  - Profit maximizing reserve: 50 MW
  - Profit maximizing power: 0 MW
- Generator 3
  - Reserve earns profit of 10 $/MWh, power earns profit of 10 $/MWh
  - Profit maximizing reserve + power = 100 MW

Table of Contents

Sequential Markets for Reserve and Energy

Sequential auctions for energy and reserves:

- First step: trade reserves
- Second step: trade energy

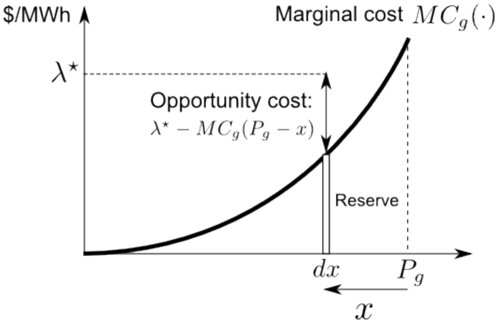
Example

- Three generators
  - $P_1 = 100$ MW, $R_1 = 1$ MW/minute, $MC_1 = 10$ \$/MWh
  - $P_2 = 100$ MW, $R_2 = 5$ MW/minute, $MC_2 = 80$ \$/MWh
  - $P_3 = 100$ MW, $R_1 = \infty$, $MC_3 = 0$ \$/MWh
- Inelastic demand $D = 100$ MW
- Secondary reserve (10 minutes) $R = 100$ MW

Suppose all agents believe the energy price will be $\lambda^\star$ and bid truthfully, generator g bids **opportunity cost**:

$$\max(\lambda^\star - MC_g, 0) \text{ \$/MWh}$$

Opportunity Cost



Allocate slice *dx* for reserves, instead of using it to sell energy at a price $\lambda^\star \Rightarrow$ opportunity cost:

$$\max(0, \lambda^\star - MC_g(P_g - x))$$

Reserve uniform price auction:

- Generator 2 cleared for 50 MW
- Generator 1 cleared for 10 MW
- Generator 3 cleared for 40 MW

Energy uniform price auction:

- Generator 1: 90 MW at 10 $/MWh
- Generator 2: 50 MW at 80 $/MWh
- Generator 3: 60 MW at 0 $/MWh

Energy market clearing price: $\lambda^\star = $ 10 $/MWh

Returning to reserve auction, we find that $\mu^\star = $ 10 $/MWh (verify this)

Table of Contents

Market Design for Reserve Auctions

We saw that sequential clearing of reserves and energy is equivalent to simultaneous clearing

- Should the auctions be pay as bid or uniform price?
- Should the auctions for different reserves be simultaneous or sequential?

Complicating factor: substitutability
Primary reserve $\succ$ secondary reserve $\succ$ tertiary reserve

Example

- Primary reserve demand: 400 MW
- Secondary reserve demand: 350 MW
- Bid 1: 600 MW primary reserve at 10 $/MWh
- Bid 2: 50 MW primary reserve at 15 $/MWh
- Bid 3: 25 MW secondary reserve at 5 $/MWh
- Bid 4: 400 MW secondary reserve at 20 $/MWh

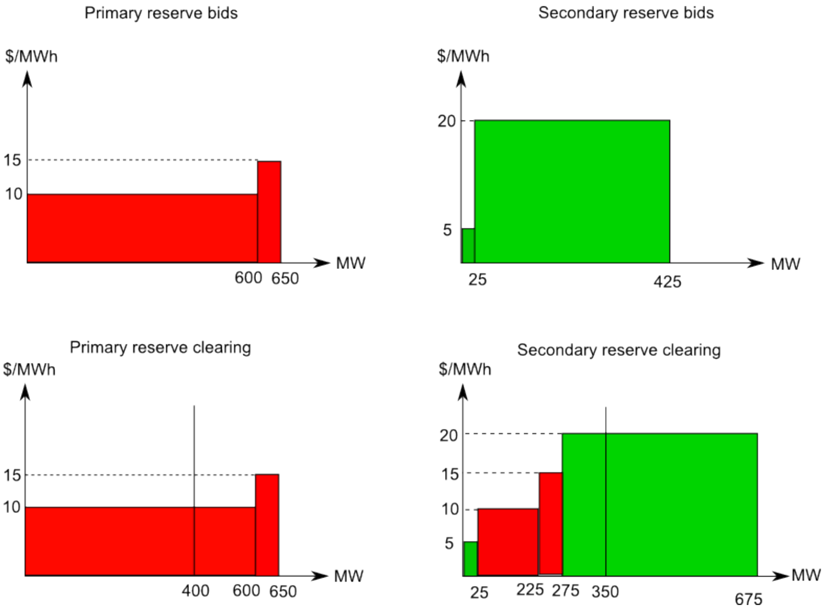
We will consider three auction designs:

1. Cascading 1
2. Cascading 2
3. Simultaneous clearing

Cascading 1

- Clearing of primary reserves → cascade of leftover bids → clearing of secondary reserves
- Uniform price based on most expensive accepted bid in current auction

- Primary reserve price: 10 $/MWh
- Secondary reserve price: 20 $/MWh
- Price reversal (this is bad)
- Cost: 8375 $/h
- Payment: 11000 $/h



Primary reserve bids
$/MWh
15
10
600
650
MW
Secondary reserve bids
$/MWh
20
5
25
425
MW
Primary reserve clearing
$/MWh
15
10
400
600
650
MW
Secondary reserve clearing
$/MWh
20
15
10
5
25
225
275
350
675
MW

Cascading 2

- Clearing of primary reserves $\rightarrow$ cascade of leftover bids $\rightarrow$ clearing of secondary reserves
- Uniform price based on most expensive accepted bid in current or inferior auctions

- Primary reserve price: 15 \$/MWh
- Secondary reserve price: 20 \$/MWh
- Price reversal
- Cost: 8375 \$/h
- Payment: 13000 \$/h

Simultaneous Clearing

$$
\begin{aligned}
(Res): \quad & \min \sum_{g \in G} \int_0^{r1_{g,1}+r1_{g,2}+r2_g} MC_g(x)dx \\
(\mu 1): \quad & \sum_{g \in G} r1_{g,1} \geq R1 \\
(\mu 2): \quad & \sum_{g \in G} (r1_{g,2} + r2_g) \geq R2 \\
(\rho 1_g): \quad & r1_{g,1} + r1_{g,2} \leq R1_g \\
(\rho 2_g): \quad & r2_g \leq R2_g \\
& r1_{g,1}, r1_{g,2}, r2_g \geq 0
\end{aligned}
$$

A simultaneous uniform pricing auction for reserves is conducted as follows:

- Suppliers submit incremental bids for reserves: price-quantity pairs that indicate the amount of reserves that they are willing to provide for a given price
- The market operator solves (*Res*) and announces μ1 as the uniform price for primary reserve, μ2 as the price for secondary reserve

No Price Reversal

In the simultaneous uniform price auction the price for higher quality reserve is higher: $\mu 1 \geq \mu 2$

Proof: Since $R1 > 0$, $r1_{g,1} > 0$ for some g
From

$$0 \leq r1_{g,1} \perp MC_g(r1_{g,1} + r1_{g,2} + r2_g) - \mu 1 + \rho 1_g \geq 0$$

it follows that

$$\mu_1 = MC_g(r1_{g,1} + r1_{g,2} + r2_g) + \rho 1_g$$

From

$$0 \leq r1_{g,2} \perp MC_g(r1_{g,1} + r1_{g,2} + r2_g) - \mu 2 + \rho 1_g \geq 0$$

it follows that

$$\mu_2 \leq MC_g(r1_{g,1} + r1_{g,2} + r2_g) + \rho 1_g = \mu_1$$

- Primary reserve price: 20 $/MWh
- Secondary reserve price: 20 $/MWh
- Cost: 8375 $/h
- Payment: 15000 $/h

Criticism: high payments to generators, in order to induce them to bid truthfully

Table of Contents

What is Balancing?

Balancing is the task of *adjusting* power production and consumption in *real time*

What does this have to do with reserve? Balancing is offered by

- **Balancing responsible parties (BRPs)**: resources that have committed to offer *reserve*. Reserves are obliged to offer an amount of power at least equal to the amount of their promised reserve capacity
- **Free bids**: resources that offer balancing energy without being obliged to do so

Increment / Decrement Bids

To run a balancing market using increment / decrement bids:

- collect bids by resources that can adjust their production or consumption in real time
- activate these resources in order to relieve any imbalances
- charge market participants who deviate from their earlier positions

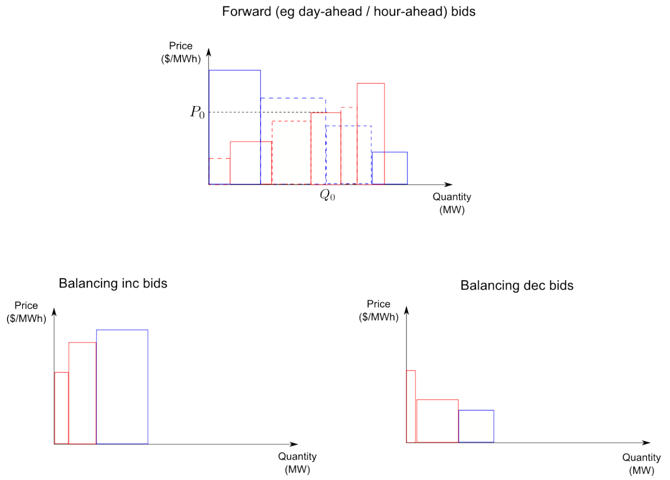
Logic of Increment / Decrement Bids

Suppose that a resource has been cleared for Q_0 MW at Q_0 \$/MWh in the day-ahead market

What if the resource would like to trade one more time (in the balancing market)?

- Upward change in production / downward change in consumption is paid from the balancing market to the resource $\rightarrow$ **increment bid**
- Downward change in production / upward change in consumption is paid from the resource to the balancing market $\rightarrow$ **decrement bid**

Example of Balancing Market Clearing



- Blue bids: consumers
- Red bids: generators
- Dashed border: inflexible resources
- Solid border: flexible resources that participate in balancing market
- Lower left figure: increment bids
- Lower right figure: decrement bids

The Example in Numbers

Supply offer	Marg. cost ($/MWh)	Quantity (MW)	Flexible?
S1	25	40	No
S2	40	80	Yes
S3	60	80	No
S4	70	50	Yes
S5	75	40	No
S6	100	50	Yes
Demand offer	**Valuation ($/MWh)**	**Quantity (MW)**	**Flexible?**
D1	110	100	Yes
D2	80	120	No
D3	55	90	No
D4	30	70	Yes

The Example in Numbers

Inc offer	Marg. cost ($/MWh)	Quantity (MW)
Inc1	70	30
Inc2	100	50
Inc3	110	100
Dec offer	Valuation ($/MWh)	Quantity (MW)
Dec1	70	20
Dec2	40	80
Dec3	30	70

Example Explained

The first market clears at a price of 70 $/MWh at a quantity of 220 MW

For the balancing market:

- Inc1 originates from bid S4 (flexible resource and for which 30 MW have yet to be cleared)
- Inc2 corresponds to bid S6
- Inc3 corresponds to bid D1
- Dec1 originates from the 20 MW of bid S4 that have already been cleared
- Dec2 corresponds to S2
- Dec3 corresponds to D4

Notation for Balancing Market Model

- D: set of decrement bids
- U: set of increment bids
- MB_d: marginal benefit of decrement bid d
- Δ_d: offered quantity of decrement bid
- MC_u: marginal cost of increment bid u
- Δ_u: offered quantity of increment bid u
- δ^+ [respectively δ^-]: amount of upward [respectively downward] activation that is cleared in the balancing market
- Δ: demand for upward or downward activation (can be positive or negative)

Balancing Market Model

$$\max \sum_{d \in D} MB_d \delta_d^- - \sum_{u \in U} MC_u \delta_u^+$$

$$\sum_{u \in U} \delta_u^+ - \sum_{d \in D} \delta_d^- = \Delta$$

$$\delta_u^+ \leq \Delta_u, u \in U$$

$$\delta_d^- \leq \Delta_d, d \in D$$

$$\delta_u^+, \delta_d^- \geq 0, u \in U, d \in D$$

And Suddenly ... the Unexpected Happens - Balancing Market Clearing

Suppose the generator offering bid S3 fails

Using increment bids:

- Shortage of 80 MW (inelastic demand for 80 MW upward reserve)
- Referring to increment bids, market clearing price is 100 $/MWh (or any price between 100 - 110 $/MWh)
- Bids Inc1 and Inc2 are fully accepted, bid Inc3 is fully rejected

And Suddenly ... the Unexpected Happens - Economic Dispatch Clearing

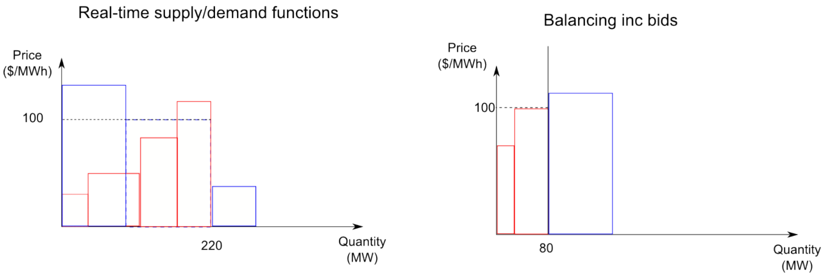
Suppose the generator offering bid S3 fails

Using economic dispatch:

- Bid S3 is absent because the unit has failed
- Bid S5 is absent because it was not accepted in an earlier market and is not flexible
- Bid D3 is absent because it was not accepted in an earlier market and is not flexible
- Bids Inc1 and Inc2 are fully accepted, bid Inc3 is fully rejected

Important observation: clearing inc/dec bids is equivalent to clearing entire supply/demand functions

Graphical Illustration



Real-Time Supply and Demand Bids

Supply offer	Marg. cost ($/MWh)	Quantity (MW)
S1	25	40
S2	40	80
S4	70	50
S6	100	50
Demand offer	Valuation ($/MWh)	Quantity (MW)
D1	110	100
D2	80	120
D4	30	70