Resource Adequacy and Operational Security Interaction in the EPOC 2030-50 Project

Contents

1. Interaction description

All code can be found at https://github.com/junglegobs/ASoSEPOC.

2. Description of a Deterministic Unit Commitment Model with Probabilistic Reserve (DUC-PR) constraints

2.1. Sets

- G - Generators
- G_n - Generators located at node n
- GD - Dispatchable / thermal / conventional generators
- GR - Renewable / variable generators
- N - Nodes or buses in the network
- B - Lines or branches
- T - Time steps / intervals / slices
- L^+ - Upward reserve levels
- L^- - Downward reserve levels

2.2. Parameters

- D_{nt} - Demand
- $PTDF_{nl}$ - Power Transfer Distribution Factor
- AF_{gt} - Availability Factor
- K_g - Capacity
- P_g^{min} - Minimum power output
- P_g^{max} - Maximum power output
- $D_{lt}^{L^+}$ - Upward reserve requirement
- $D_{lt}^{L^-}$ - Downward reserve requirement

2.3. Variables

All variables are positive apart from injetion variables which may also be negative.

- q_{gt} - Generation
- $\hat{q}_{gt}$ - Generation above the minimum stable operating point (0 in the case of renewables).
- ls_{nt} - Load shedding
- inj_{nt} - Node injection
- f_{lt} - Branch flow
- r^+_{gt} - Total upward reserve provision
- r^-_{gt} - Total downward reserve provision
- $r^{L^+}_{glt}$ - Upward reserve provision for reserve level l
- $r^{L^-}_{glt}$ - Downward reserve provision for reserve level l
- rs_{nlt} - Upward reserve shedding for reserve level l
- rc_{nlt} - Downward reserve provided by day ahead load shedding for reserve level l
- $rinj^{L^+}_{nlt}$ - Possible node injection due to activation of upward reserve level l
- $rinj^{L^-}_{nlt}$ - Possible node injection due to activation of downward reserve level l
- $rf^{L^+}_{nbt}$ - Possible branch flow due to activation of upward reserve level l
- $rf^{L^-}_{nbt}$ - Possible branch flow due to activation of downward reserve level l
- $d^{L^+}_{nlt}$ - Possible imbalance on node n for upward reserve level l
- $d^{L^-}_{nlt}$ - Possible imbalance on node n for downward reserve level l

2.4. Objective

$$\begin{aligned}
\min \quad & \sum_{t\in T}\sum_{g\in G} C^{var}_g \cdot \hat{q}_{gt} \\
& + \sum_{t\in T}\sum_{l\in L^+}\sum_{n\in N} P^{L^+} \cdot \sum_{g\in G} C^{var}_g \cdot r^{L^+}_{glt} + C^{shed} \cdot rs_{nlt} \\
& - \sum_{t\in T}\sum_{l\in L^-}\sum_{n\in N} P^{L^-} \cdot C^{var}_g \cdot r^{L^-}_{gnlt} + C^{shed} \cdot rc_{nlt}
\end{aligned} \tag{1}$$

From the top line to the bottom, the costs are those of dispatching generators and activating upwards or downwards reserves.

Costs related to unit commitment, z_{gt}, have been omitted for brevity though they are included in the model.

2.5. Constraints

The power balance:

$$\sum_{g \in G_n} q_{gt} + ls_{nt} = D_{nt} + inj_{nt} \quad n \in N, \ t \in T \tag{2}$$

Note the use of the set G_n to only allow generators at node n to contribute to the power balance. Another way of describing this would have been through an incidence matrix.

Network constraints:

$$f_{bt} = \sum_{n \in N} PTDF_{nb} \cdot inj_{nt} \quad b \in B, \ t \in T \tag{3}$$

$$-F_b \leq f_{bt} \leq F_b \quad b \in B, \ t \in T \tag{4}$$

$$\sum_{n \in N} inj_{nt} = 0 \quad n \in N, \ t \in T \tag{5}$$

$$\tag{6}$$

Constraints on generator output:

$$q_{gt} - r^-_{gt} \geq 0 \quad g \in GR, \ t \in T \tag{7}$$

$$q_{gt} + r^+_{gt} \leq AF_{gt} \cdot K_g \quad g \in GR, \ t \in T \tag{8}$$

$$q_{gt} - r^-_{gt} \geq P^{min} \cdot z_{gt} \quad g \in GD, \ t \in T \tag{9}$$

$$q_{gt} + r^+_{gt} \leq P^{max} \cdot z_{gt} \quad g \in GD, \ t \in T \tag{10}$$

For brevity and clarity, constraints on ramping and minimum up and down times are omitted.

The constraints on reserve provision are as follows:

$$D^{L^+}_{lt} = \sum_{g \in G} r^{L^+}_{glt} + \sum_{n \in N} rs_{nlt} \quad l \in L^+, \ t \in T \tag{11}$$

$$D^{L^-}_{lt} = \sum_{g \in G} r^{L^-}_{glt} + \sum_{n \in N} rc_{nlt} \quad l \in L^-, \ t \in T \tag{12}$$

$$\sum_{l \in L^-} rc_{nlt} \leq ls_{nt} \quad n \in N, \ t \in T \tag{13}$$

$$r^+_{gt} = \sum_{l \in L^+} r^{L^+}_{gnlt} \quad g \in G, \ t \in T \tag{14}$$

$$r^-_{gt} = \sum_{l \in L^-} r^{L^-}_{gnlt} \quad g \in G, \ t \in T \tag{15}$$

The amount of reserve shedding can be limited to a fraction of the total upward reserve requirements RSL:

$$\sum_{n\in N, l\in L^+} rs_{nlt} \leq RSL \cdot \sum_{l\in L^+} D^{L^+}_{l't} \quad t \in T \tag{16}$$

There are several matters to note here:

- The operating reserve balance is performed over the entire network, not per node.
- The operating reserve balance is split into reserve levels. Higher reserve levels (values of l) are less likely to occur.
- It is possible to shed upward reserves, and this is more likely to occur for higher reserve levels. This model is therefore able to make a trade-off between day ahead adequacy and real time operational security, albeit crudely.
- Shedding load in day ahead allows additional downward reserves to be provided through the variable rc_{nlt}. Implicitly this assumes that load can be 'activated' in real time to provide downward reserves.

The following constraints attempt to take network constraints into account (albeit very weakly):

$$\sum_{g\in G_n, l'=1:l} (r^{L^+}_{glt} + rs_{nlt}) = d^{L^+}_{nlt} + rinj^{L^+}_{nlt} \quad n \in N,\ l \in L^+,\ t \in T \tag{17}$$

$$-\sum_{g\in G_n, l'=1:l} (r^{L^-}_{glt} + rc_{nlt}) = d^{L^-}_{nlt} + rinj^{L^-}_{nlt} \quad n \in N,\ l \in L^-,\ t \in T \tag{18}$$

$$\sum_{n\in N} d^{L^+}_{nlt} = \sum_{l'=1:l} D^{L^+}_{l't} \quad l \in L^+,\ t \in T \tag{19}$$

$$\sum_{n\in N} d^{L^-}_{nlt} = -\sum_{l'=1:l} D^{L^-}_{l't} \quad l \in L^-,\ t \in T \tag{20}$$

$$rf^{L^+}_{blt} = \sum_{n\in N} PTDF_{nb} \cdot rinj^{L^+}_{nlt} \quad b \in B,\ l \in L^+,\ t \in T \tag{21}$$

$$rf^{L^-}_{blt} = \sum_{n\in N} PTDF_{nb} \cdot rinj^{L^-}_{nlt} \quad b \in B,\ l \in L^-,\ t \in T \tag{22}$$

$$-F_b \leq f_{bt} + rf^{L^+}_{blt} \leq F_b \quad b \in B,\ l \in L^+,\ t \in T \tag{23}$$

$$-F_b \leq f_{bt} + rf^{L^-}_{blt} \leq F_b \quad b \in B,\ l \in L^-,\ t \in T \tag{24}$$

$$\sum_{n\in N} rinj^{L^+}_{nt} = 0 \quad l \in L^+,\ n \in N,\ t \in T \tag{25}$$

$$\sum_{n\in N} rinj^{L^-}_{nt} = 0 \quad l \in L^-,\ n \in N,\ t \in T \tag{26}$$

Since imbalances are aggregated across the network, a particular reserve level activation is not associated with an imbalance at the nodal level. The above constraints therefore enforce that for each reserve level l and node n, there exists some combination of nodal imbalance, node injections, generator dispatches and line flows which would satisfy the network constraints AND the imbalance across the entire network.

Given the formulation here, which uses reserve levels, i.e. quantiles, over the entire network to represent forecast errors, it is difficult to come up with more stringent conditions. However, we devised two ways of doing so. The first is to apply box constraints to the possible nodal imbalances:

$$d_{nt}^{min} \leq d_{nlt}^{L^+} \leq d_{nt}^{max} \quad n \in N,\ l \in L^+,\ t \in T \tag{27}$$

$$d_{nt}^{min} \leq d_{nlt}^{L^-} \leq d_{nt}^{max} \quad n \in N,\ l \in L^-,\ t \in T \tag{28}$$

It is possible to calculate d_{nt}^{min} and d_{nt}^{max} since the quantiles for D^{L^+} and D^{L^-} are calculated based on forecast error scenarios which are defined at the nodal level. These limits are shown in Figure 1. Clearly it is simply not possible to have an imbalance on some nodes, such as Coo (the location of Belgium's pumped hydro unit). Constraining $d_{nlt}^{L^+}$ and $d_{nlt}^{L^-}$ in this way is referred to as AbsImb later on.

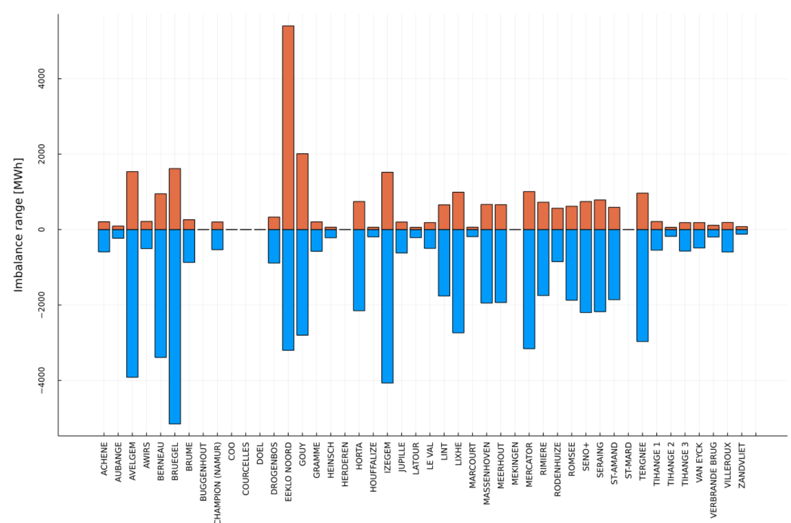

Figure 1: Range of possible imbalances for all hours of day 309.

The other possibility is to restrict $d_{nlt}^{L^+}$ and $d_{nlt}^{L^-}$ to lie within the convex hull of all imbalances. This is illustrated in 2 dimensions in Figure 2 for the imbalances at Tihange 1 and 2. Clearly the imbalances are highly correlated, and constraining the possible nodal imbalances to lie within the convex hull exploits this in a way that box constraints would not be able to.

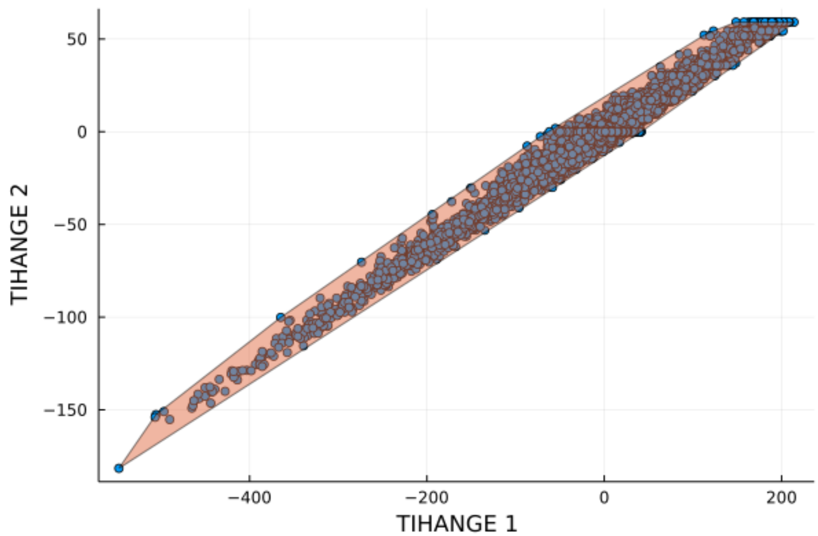

Figure 2: Illustration of convex hull constraints on d^{L+}_{nlt} and d^{L-}_{nlt}. Shaded area is the convex hull, d^{min}_{nt} and d^{max}_{nt} are the x limits for TIHANGE 1 and the y limits for TIHANGE 2.

3. Input data - stylised Belgian grid with a large amount of variable renewable energy sources

For now, see README.md

4. Analysis of DUC-PR model results

This analysis relates only to the 309th day of the year (November 5th).

4.1. No operating reserves

Table 1 lists results for an increasing level of technical constraints or increasingly inflexible system. While the objective more than doubles going from the simple linear economic dispatch model with no network constraints to the unit commitment model with network constraints, no load shedding occurs. Preventing simultaneous charging and discharging constraints does not affect results at all, implying that additional energy consumption from storage does not aid congestion.

4.2. Probabilistic operating reserves with no reserve activation network constraints

- Unit commitment constraints lead to unavoidable load shedding.
- This result should be interpreted with caution however, since reserve provision is quite strict (storage can't provide reserves, non spinning reserves not modelled). If more flexibility would be available in terms of reserve provision then this might not occur.

UC	DANet	PSCD	Load shedding [MWh]	Objective
			0.0	101,916
✗			0.0	212,558
✗	✗		0.0	252,327
✗	✗	✗	0.0	252,327

Table 1: Analysis of model results when operating reserves are not included. UC = Unit Commitment constraints, DANet = Day Ahead Network constraints, PSCD = Prevent Simultaneous Charging and Discharging constraints.

- Network constraints are less problematic than unit commitment (cost increase of 20,000 euros instead of 500,000) (perhaps thanks to storage, who knows).
- Preventing simultaneous charge and discharge has a small but noticeable effect.

UC	DANet	PSCD	RSL	Load shedding [MWh]	Reserve Shedding [MWh]	Objective
			0.0	0.0	0.0	117,290
			0.5	0.0	0.0	117,290
			1.0	0.0	0.0	117,290
✗			0.0	1,669	0.0	645,679
✗			0.5	1,669	0.0	645,679
✗			1.0	1,669	0.0	645,679
✗	✗		0.0	1,669	0.0	665,010
✗	✗		0.5	1,669	136	657,010
✗	✗		1.0	1,669	136	657,010
✗	✗	✗	0.0	1,669	0.0	665,705
✗	✗	✗	0.5	1,669	136	665,696
✗	✗	✗	1.0	1,669	136	665,696

Table 2: Analysis of model results with operating reserves but no reserve activation network constraints. UC = Unit Commitment constraints, DANet = Day Ahead Network constraints, PSCD = Prevent Simultaneous Charging and Discharging constraints, RSL = Reserve Shedding Limit.

4.3. Probabilistic operating reserves with reserve activation network constraints

UC	DANet	PSCD	RSL	AbsImb	Load shedding [MWh]	Reserve Shedding [MWh]	Objective

Table 3: Analysis of model results with operating reserves but no reserve activation network constraints. UC = Unit Commitment constraints, DANet = Day Ahead Network constraints, PSCD = Prevent Simultaneous Charging and Discharging constraints, RSL = Reserve Shedding Limit, AbsImb = limit on absolute value of nodal imbalances