3.2.1 Sequential market clearing model (SeqM): inefficient transmission allocation

According to the current practice, reserve capacity, day-ahead and balancing markets are cleared in sequential and independent auctions. Let RR_a^+/RR_a^- denote the upward/downward reserve requirements for each area $a \in A$ of the system and χ_e the percentage of inter-area interconnection capacity T_e of link e allocated to reserves exchange. Taking these values as input parameters, the reserve capacity market aims at minimizing the total procurement cost $\mathcal{C}^R$ of upward r_{ia}^+ and downward r_{ia}^- capacity from a pool of common resources $i \in I$ that are available to all system areas. The reserve capacity costs C_i^+ and C_i^- reflect the opportunity cost that generators incur from operating at a set-point different than their optimal day-ahead energy production. The reserve capacity market clearing is formulated as:

$$\underset{\Phi^R}{\text{Minimize}}\, \mathcal{C}^R = \sum_{a \in A} \sum_{i \in I} \left(C_i^+ r_{ia}^+ + C_i^- r_{ia}^- \right) \tag{3a}$$

subject to

$$\sum_a r_{ia}^+ \leq R_i^+, \quad \forall i, \tag{3b}$$

$$\sum_a r_{ia}^- \leq R_i^-, \quad \forall i, \tag{3c}$$

$$\sum_i r_{ia}^+ \geq RR_a^+, \quad \forall a, \tag{3d}$$

$$\sum_i r_{ia}^- \geq RR_a^-, \quad \forall a, \tag{3e}$$

$$\sum_{i \in \mathcal{M}_{a_s(e)}^I} r_{ia_r(e)}^+ \leq \chi_e T_e, \quad \forall e, \tag{3f}$$

$$\sum_{i \in \mathcal{M}_{a_r(e)}^I} r_{ia_s(e)}^+ \leq \chi_e T_e, \quad \forall e, \tag{3g}$$

$$\sum_{i \in \mathcal{M}_{a_s(e)}^I} r_{ia_r(e)}^- \leq \chi_e T_e, \quad \forall e, \tag{3h}$$

$$\sum_{i \in \mathcal{M}_{a_r(e)}^I} r_{ia_s(e)}^- \leq \chi_e T_e, \quad \forall e, \tag{3i}$$

$$r_{ia}^+, r_{ia}^- \geq 0, \quad \forall i, \forall a, \tag{3j}$$

where $\Phi^R = \{r_{ia}^+, r_{ia}^-, \forall i, \forall a\}$ is the set of optimization variables. Constraint (3b) ensures that the provision of upward reserves from unit i to all areas a of the power system does not exceed its upward capacity offer R_i^+. Similarly, constraint (3c) enforces the capacity offer limit R_i^- for downward reserve provision. The upward RR_a^+ and downward RR_a^- area reserve requirements are enforced by constraints (3d) and (3e), respectively. The set of constraints (3f), (3g) models the upper bounds of upward reserves exchange between the sending $a_s(e)$ and receiving $a_r(e)$ areas of link e. The amount of upward reserves r_{ia}^{+} procured by area a from unit i which is physically located in area a', i.e., subset of units $i \in \mathcal{M}_{a'}^{I}$, should not exceed the inter-area exchange limit $\chi_e T_e$, where χ_e is the percentage of link capacity T_e allocated to reserves trade. The same principle applies also for downward reserves exchange limits enforced by constraints (3h), (3i). In line with the zonal network representation of reserves markets, the transmission capacity T_e of link e is the aggregated flow limit of all tie-lines between areas $a_s(e)$ and $a_r(e)$ given as:

$$T_e = \sum_{\ell \in \Lambda_{a_r(e)}^{a_s(e)}} T_\ell, \quad \forall e, \tag{4}$$

where $\Lambda_{a_r(e)}^{a_s(e)}$ is the set of AC and HVDC lines connecting areas $a_s(e)$ and $a_r(e)$ across link e. Finally, constraints (3j) constitute variable declarations.

Currently the size of reserve requirements in each region of the system is determined by the corresponding operator according to the dimensioning rules defined on the European level [11,17]. These rules follow a deterministic philosophy that ensures enough reserves to supply a predefined percentage of hourly load and fulfill a set of static reliability criteria, i.e., N−1 security constraint violations. However, this approach disregards the structure of renewables' uncertainty and its impact on operational costs and system reliability. Taking into account these considerations, reserve requirements can alternatively be determined using a probabilistic description of system uncertainties that perform a trade-off between risk and reserve cost [14,36]. The percentage χ of tie-line capacity that becomes available during the reserve capacity market clearing can be determined according to methods presented in Sect. 2.3.

Once the optimal reserve procurement $(\hat{r}_{ia}^{-}, \hat{r}_{ia}^{+})$ is defined, the day-ahead schedule that minimizes the energy production costs $\mathcal{C}^D$ in (5a), based on the price offers C_i from the conventional generators, is given as the solution to following optimization problem:

$$\underset{\Phi^D}{\text{Minimize}}\, \mathcal{C}^D = \sum_{i \in I} C_i p_i \tag{5a}$$

subject to

$$\sum_{j \in \mathcal{M}_n^J} w_j + \sum_{i \in \mathcal{M}_n^I} p_i - D_n - \sum_{\ell \in L^{\mathrm{AC}}} A_{\ell n} f_\ell - \sum_{\ell \in L^{\mathrm{DC}}} A_{\ell n} z_\ell = 0, \quad \forall n, \tag{5b}$$

$$\sum_a \hat{r}_{ia}^{-} \leq p_i \leq P_i - \sum_a \hat{r}_{ia}^{+}, \quad \forall i, \tag{5c}$$

$$0 \leq w_j \leq \overline{W}_j, \quad \forall j, \tag{5d}$$