TSO–DSO Coordination and Market Power in Sequential Electricity and Ancillary Services Markets: Equilibrium Models Under Load and Renewable Generation Uncertainty

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Context

- The **need for flexibility services** is increasing due to the growing integration of renewable energy sources (RES) into transmission and distribution networks.

- Currently, only **programmable generation units** connected to **transmission** networks can provide ancillary services.

- The viability of **opening flexibility markets to Distributed Energy Resources (DERs)** is being assessed by several European countries through pilot projects.

- Aim: identify market structures that enable efficient management of flexibility services, while **minimising their cost**

The issue of market power

- ➢ The electricity Day-Ahead Market (DAM) and the Ancillary Services Market (ASM) are cleared in sequence: **multiple markets in a cascade** may provide participants with opportunities to exert market power (Allaz-Vila, 1993).

- ➢ Only a limited number of participants operate in energy markets (**oligopolies**).

- ➢ The radial topology of distribution networks can greatly reduce the **number of resources that can resolve congestion** in a given branch.

⇒ **Significant cost increases for the system** may result from strategic market players increasing
⇒ their profit by exerting market power.

Our contribution

- We have developed mathematical programming models that **represent oligopolistic competition** between market participants in sequential energy markets under **various coordination schemes between the ASMs** operated in transmission (**TSO**) and in distribution (**DSOs**).
- We formulate the problem as a **game**, in which each participant has his own optimisation target.
- We then determine the **Nash equilibrium**, i.e. a solution from which no participant would unilaterally deviate.

These models' simulations may help regulators compare the coordination schemes being proposed in terms of the ability to exert market power and related costs.

We have modelled the following coordination schemes between the TSO and the DSOs

A. **A common ASM** for transmission and distribution, in which all flexibility resources participate, whether they are connected to the transmission or distribution network.

B. **Separate ASMs for transmission and distribution**, in which each resource only participates in the ASM of the network to which it is connected.

C. **Separate ASMs for transmission and distribution**:
    1. ASMs of distribution networks are cleared first
    2. any distribution resources not used in distribution are bid in the transmission network ASM.

Development of the MILP simulation model

for the bidding problem of a Participant in DAM and ASM

under **coordination scheme A** (unique ASM for the system)

Let $\mathcal{I}$ denote the set of participants in DAM and ASM, also called Aggregators.

Aggregator $i \in \mathcal{I}$ manages

- the set $\mathcal{U}_i$ of **programmable power plants**, with G_u installed capacity of plant $u \in \mathcal{U}_i$
- the set $\mathcal{N}_i$ of **flexible loads**, with δ_n maximum fraction that can be curtailed

Aggregator i submits to **DAM** a sale bid for each programmable power plant $u \in \mathcal{U}_i$:

- the **bid quantity** equals the plant capacity G_u, as we assume that Aggregators compete on prices
- the **bid price** $b_u^{\mathcal{U}}$: decision of Aggregator i

The DAM Operator, given

- the forecasted load D_n at each node $n \in \mathcal{N}$,
- the forecasted power output W_r of each non-programmable RES power plant $r \in \mathcal{R}$, and
- the sale bids submitted
  - by Aggregator i: $(G_u, b_u^{\mathcal{U}})$, $u \in \mathcal{U}_i$
  - by the competitors: $(G_u, b_u^{\mathcal{U}})$, $u \in \mathcal{U} \backslash \mathcal{U}_i$ **(*)**

clears the market, determining the accepted quantities g_u, $u \in \mathcal{U}$, and the clearing price λ **(**)**

(*) $\mathcal{U}$: set of all programmable power plants in the system

(**) This model refers to a bus-bar Day-Ahead Market (as it is in France, Germany, Spain,…).

In Italy, Norway and Sweden, the DAM markets are divided into zones due to their geographical shape.

- **Real-time load** $\widetilde{D}_n$ at each node $n \in \mathcal{N}$ and **real-time power output** $\widetilde{W}_r$ of non-programmable power plants $r \in \mathcal{R}$ may **differ from forecasts** D_n and W_r.

- **Network congestions** may occur.

These issues are solved by the ASMs: their Participants submit the following bids

- for each programmable power plant $u \in \mathcal{U}$

	$u \in \mathcal{U}_i$	$u \in \mathcal{U} \backslash \mathcal{U}_i$
• an **up-regulation** bid:	$\left(G_u - g_u, b_u^{\mathcal{U},\uparrow}\right)$	$\left(G_u - g_u, b_u^{\mathcal{U},\uparrow}\right)$
• a **down-regulation** bid:	$\left(g_u, b_u^{\mathcal{U},\downarrow}\right)$	$\left(g_u, b_u^{\mathcal{U},\downarrow}\right)$

- for each flexible load $n \in \mathcal{N}$

	$n \in \mathcal{N}_i$	$n \in \mathcal{N} \backslash \mathcal{N}_i$
• a **load curtailment** bid:	$\left(\delta_n \widetilde{D}_n, b_n^{\mathcal{N},\downarrow}\right)$	$\left(\delta_n \widetilde{D}_n, b_n^{\mathcal{N},\downarrow}\right)$

The ASM Operator determines

- the accepted quantities $g_{u,s}^{\uparrow}$ (up-regulation) and $g_{u,s}^{\downarrow}$ (down-regulation), $u \in \mathcal{U}$,
- the load curtailments $d_{n,s}^{\downarrow}$, $n \in \mathcal{N}$, and
- the power output curtailments $w_{r,s}^{\downarrow}$ of RES power plants $r \in \mathcal{R}$

to solve **network congestions** and **imbalances** between load and generation.

We assume that each Aggregator $i \in \mathcal{I}$

- selects each bid price from a finite number of alternative values:

  $b_u^{\mathcal{U}}$ is selected from the set $\left\{B_{u,a}^{\mathcal{U}}, a \in \mathcal{A}_u^{\mathcal{U}}\right\}$

  [$b_u^{\mathcal{U},\uparrow}$ from $\left\{B_{u,a}^{\mathcal{U},\uparrow}, a \in \mathcal{A}_u^{\mathcal{U},\uparrow}\right\}$, $b_u^{\mathcal{U},\downarrow}$ from $\left\{B_{u,a}^{\mathcal{U},\downarrow}, a \in \mathcal{A}_u^{\mathcal{U},\downarrow}\right\}$ and $b_n^{\mathcal{N},\downarrow}$ from $\left\{B_{n,a}^{\mathcal{N},\downarrow}, a \in \mathcal{A}_n^{\mathcal{N},\downarrow}\right\}$]

- knows the pricing strategies of the competitors, as observed in the market

- takes into account the **uncertainty of real-time loads and of real-time power outputs of RES**, representing the uncertainty by a set $\mathcal{S}$ of **scenarios** of loads $\left(\widetilde{D}_{n,s}\right)$ and renewable power outputs $\left(\widetilde{W}_{r,s}\right)$, with σ_s the occurrence probability of scenario s.

Thus, we formulate the bidding problem of Aggregator i by a **two-stage stochastic bilevel model**

1. **First stage variables**:
   - bid prices $\left(b_u^{\mathcal{U}}, b_u^{\mathcal{U},\uparrow}, b_u^{\mathcal{U},\downarrow}, u \in \mathcal{U}_i\right)$ and $\left(b_n^{\mathcal{N},\downarrow}, n \in \mathcal{N}_i\right)$ of Aggregator i
   - accepted quantities $(g_u, u \in \mathcal{U})$ and the clearing price (λ) determined by the DAM Operator

2. **Second stage variables**:
   - accepted quantities $\left(g_{u,s}^{\uparrow}, g_{u,s}^{\downarrow}, u \in \mathcal{U}\right)$ of up- and down-regulation bids
   - accepted quantities $\left(d_{n,s}^{\downarrow}, n \in \mathcal{N}\right)$ of load curtailment bids
   - curtailments $\left(w_{r,s}^{\downarrow}, r \in \mathcal{R}\right)$ of renewable generation

   determined by the Operator of the (common) ASM in each scenario $s \in \mathcal{S}$

The **upper level** represents the bid selection problem of Aggregator i.

The **objective function** of the upper level problem is

$$\max \underbrace{\sum_{u\in\mathcal{U}_i}(\lambda - C_u)\, g_u}_{\text{profit on DAM}} + \underbrace{\sum_{s\in\mathcal{S}} \sigma_s \left\{ \sum_{u\in\mathcal{U}_i} \left[\left(b_u^{\mathcal{U},\uparrow} - C_u^{\uparrow}\right) g_{u,s}^{\uparrow} + \left(C_u^{\downarrow} - b_u^{\mathcal{U},\downarrow}\right) g_{u,s}^{\downarrow} \right] + \sum_{n\in\mathcal{N}_i} \left(b_n^{\mathcal{N},\downarrow} - \lambda\right) d_{n,s}^{\downarrow} \right\}}_{\text{expected profit on }\textbf{ASM}}$$

$u \in \mathcal{U}_i$	C_u	generation cost	
	λ	clearing price	**decided** by DAM Operator (**lower** level problem)
$u \in \mathcal{U}_i$	g_u	accepted quantity	

$u \in \mathcal{U}_i$	$C_u^{\uparrow}, C_u^{\downarrow}$	cost of upward and downward regulation	
$u \in \mathcal{U}_i$	$g_{u,s}^{\uparrow}, g_{u,s}^{\downarrow}$	accepted quantities of regulation bids	**decided** by ASM Operator (**lower** level problem)
$n \in \mathcal{N}_i$	$d_{n,s}^{\downarrow}$	load curtailment ($\delta_n > 0$: maximum fraction that can be curtailed)	

Constraints in the Upper Level: **selection of bid prices from a finite number of alternatives**

For $u \in \mathcal{U}_i$ and for $n \in \mathcal{N}_i$:

- selection of DAM bid price $b_u^{\mathcal{U}}$

$$\boxed{\begin{array}{l} b_u^{\mathcal{U}} = \sum\limits_{a \in \mathcal{A}_u^{\mathcal{U}}} B_{u,a}^{\mathcal{U}}\, x_{u,a}^{\mathcal{U}} \\[2ex] x_{u,a}^{\mathcal{U}} \in \{0,1\} \qquad a \in \mathcal{A}_u^{\mathcal{U}} \\[2ex] \sum\limits_{a \in \mathcal{A}_u^{\mathcal{U}}} x_{u,a}^{\mathcal{U}} = 1 \end{array}}$$

- selection of ASM bid prices $b_u^{\mathcal{U},\uparrow}$, $b_u^{\mathcal{U},\downarrow}$ and $b_n^{\mathcal{N},\downarrow}$

$$\boxed{\begin{array}{l} b_u^{\mathcal{U},\uparrow} = \sum\limits_{a \in \mathcal{A}_u^{\mathcal{U},\uparrow}} B_{u,a}^{\mathcal{U},\uparrow}\, x_{u,a}^{\mathcal{U},\uparrow} \\[2ex] x_{u,a}^{\mathcal{U},\uparrow} \in \{0,1\} \qquad a \in \mathcal{A}_u^{\mathcal{U},\uparrow} \\[2ex] \sum\limits_{a \in \mathcal{A}_u^{\mathcal{U},\uparrow}} x_{u,a}^{\mathcal{U},\uparrow} = 1 \end{array}}$$

$$\boxed{\begin{array}{l} b_u^{\mathcal{U},\downarrow} = \sum\limits_{a \in \mathcal{A}_u^{\mathcal{U},\downarrow}} B_{u,a}^{\mathcal{U},\downarrow}\, x_{u,a}^{\mathcal{U},\downarrow} \\[2ex] x_{u,a}^{\mathcal{U},\downarrow} \in \{0,1\} \qquad a \in \mathcal{A}_u^{\mathcal{U},\downarrow} \\[2ex] \sum\limits_{a \in \mathcal{A}_u^{\mathcal{U},\downarrow}} x_{u,a}^{\mathcal{U},\downarrow} = 1 \end{array}}$$

$$\boxed{\begin{array}{l} b_n^{\mathcal{N},\downarrow} = \sum\limits_{a \in \mathcal{A}_u^{\mathcal{U}}} B_{n,a}^{\mathcal{N},\downarrow}\, x_{n,a}^{\mathcal{N},\downarrow} \\[2ex] x_{n,a}^{\mathcal{N},\downarrow} \in \{0,1\} \qquad a \in \mathcal{A}_n^{\mathcal{N},\downarrow} \\[2ex] \sum\limits_{a \in \mathcal{A}_n^{\mathcal{N},\downarrow}} x_{n,a}^{\mathcal{N},\downarrow} = 1 \end{array}}$$

Lower Level: DAM Operator’s problem (first-stage of Aggregator i’s stochastic programming model)

$g_u \in \arg\min$		$\sum_{u\in\mathcal{U}_i} b_u^{\mathcal{U}} g_u + \sum_{u\in\mathcal{U}\setminus\mathcal{U}_i} b_u^{\mathcal{U}} g_u$		quantities g_u accepted in non-decreasing order of bid price
s.t.	$u \in \mathcal{U}$	$0 \le g_u \le G_u$	$[v_u \ge 0]$	
		$\sum_{u\in\mathcal{U}} g_u = \sum_{n\in\mathcal{N}} D_n - \sum_{r\in\mathcal{R}} W_r$	$[\lambda]$	satisfy net load (λ: clearing price)

Lower Level: DAM Operator's problem (first-stage of Aggregator i's stochastic programming model)

$g_u \in \arg\min$		$\sum_{u\in\mathcal{U}_i} b_u^{\mathcal{U}}\, g_u + \sum_{u\in\mathcal{U}\setminus\mathcal{U}_i} b_u^{\mathcal{U}}\, g_u$		quantities g_u accepted in non-decreasing order of bid price
s.t.	$u \in \mathcal{U}$	$0 \le g_u \le G_u$	$[v_u \ge 0]$	
		$\sum_{u\in\mathcal{U}} g_u = \sum_{n\in\mathcal{N}} D_n - \sum_{r\in\mathcal{R}} W_r$	$[\lambda]$	satisfy net load (λ: clearing price)

Lower Level: ASM Operator's problem in scenario $s \in \mathcal{S}$ (common ASM for networks $\mathcal{T}$ and $\mathcal{D}_k$, $1 \le k \le K$)

$\left(g_{u,s}^{\uparrow}, d_{n,s}^{\downarrow}, g_{u,s}^{\downarrow}, w_{r,s}^{\downarrow}\right)$	$\in \arg\min \sum_{u\in\mathcal{U}_i}\left(b_u^{\mathcal{U},\uparrow}\, g_{u,s}^{\uparrow} - b_u^{\mathcal{U},\downarrow}\, g_{u,s}^{\downarrow}\right) + \sum_{n\in\mathcal{N}_i} b_n^{\mathcal{N},\downarrow}\, d_{n,s}^{\downarrow} +$		
	$+ \sum_{u\in\mathcal{U}\setminus\mathcal{U}_i}\left(b_u^{\mathcal{U},\uparrow}\, g_{u,s}^{\uparrow} - b_u^{\mathcal{U},\downarrow}\, g_{u,s}^{\downarrow}\right) + \sum_{n\in\mathcal{N}\setminus\mathcal{N}_i} b_n^{\mathcal{N},\downarrow}\, d_{n,s}^{\downarrow}$		(1)
s.t. $u \in \mathcal{U}$	$0 \le g_{u,s}^{\uparrow} \le G_u - g_u$	$[\beta_{u,s} \ge 0]$	(2)
$u \in \mathcal{U}$	$0 \le g_{u,s}^{\downarrow} \le g_u$	$[\phi_{u,s} \ge 0]$	(3)
$n \in \mathcal{N}$	$0 \le d_{n,s}^{\downarrow} \le \delta_n\, \widetilde{D}_{n,s}$	$[\gamma_{n,s} \ge 0]$	(4)
$r \in \mathcal{R}$	$0 \le w_{r,s}^{\downarrow} \le \widetilde{W}_{r,s}$	$[\chi_{r,s} \ge 0]$	(5)
	$\sum_{u\in\mathcal{U}} g_{u,s}^{\uparrow} + \sum_{n\in\mathcal{N}} d_{n,s}^{\downarrow} - \sum_{u\in\mathcal{U}} g_{u,s}^{\downarrow} - \sum_{r\in\mathcal{R}} w_{r,s}^{\downarrow} = \Delta$	$[\alpha_s]$	(6)
$l \in \mathcal{L}$	$\sum_{n\in\mathcal{N}} H_{l,n}\left[\sum_{u\in\mathcal{U}_n}\left(g_u + g_{u,s}^{\uparrow} - g_{u,s}^{\downarrow}\right) + \sum_{r\in\mathcal{R}_n}\left(\widetilde{W}_{r,s} - w_{r,s}^{\downarrow}\right) - \left(\widetilde{D}_{n,s} - d_{n,s}^{\downarrow}\right)\right] \le \overline{F}_l$	$[\mu_{l,s} \ge 0]$	(7)

$$\sum_{u \in \mathcal{U}} g_{u,s}^{\uparrow} + \sum_{n \in \mathcal{N}} d_{n,s}^{\downarrow} - \sum_{u \in \mathcal{U}} g_{u,s}^{\downarrow} - \sum_{r \in \mathcal{R}} w_{r,s}^{\downarrow} = \Delta \quad (6)$$

(6) resolve **total system imbalance** $\Delta = \sum_{n \in \mathcal{N}} \left(\widetilde{D}_{n,s} - D_n \right) - \sum_{r \in \mathcal{R}} \left(\widetilde{W}_{r,s} - W_r \right)$

using resources in $\mathcal{T} \cup \mathcal{D}_1 \cup \ldots \cup \mathcal{D}_K$

$$l \in \mathcal{L} \quad \sum_{n \in \mathcal{N}} H_{l,n} \left[\sum_{u \in \mathcal{U}_n} \left(g_u + g_{u,s}^{\uparrow} - g_{u,s}^{\downarrow} \right) + \sum_{r \in \mathcal{R}_n} \left(\widetilde{W}_{r,s} - w_{r,s}^{\downarrow} \right) - \left(\widetilde{D}_{n,s} - d_{n,s}^{\downarrow} \right) \right] \leq \overline{F}_l \quad (7)$$

(7) **manage congestions** for all lines in the system $\left(\mathcal{L} = \mathcal{L}^{\mathcal{T}} \cup \mathcal{L}^{\mathcal{D}_1} \cup \ldots \cup \mathcal{L}^{\mathcal{D}_K} \right)$

$H_{l,n}$	PTDF of line l and node n
$\overline{F}_l$	maximum flow through line l

Further steps to obtain the **MILP model** of the bidding problem of Aggregator i:

- replace each (linear) lower-level problem by the corresponding **KKT conditions**

  $\Longrightarrow$ we get a **single-level (nonlinear) optimization model**

- **linearize the bilinear terms** in complementarity constraints and in objective function

  $\Longrightarrow$ we get a **MILP model**

Iterative procedure to determine a Nash equilibrium solution

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Assign initial values to bid prices of all resources: $\left(b_u^{\mathcal{U}}, b_u^{\mathcal{U},\uparrow}, b_u^{\mathcal{U},\downarrow}\right)_{k=0}$, $u \in \mathcal{U}$, and $\left(b_n^{\mathcal{N},\downarrow}\right)_{k=0}$ $n \in \mathcal{N}$.

For $k = 1, \dots, Kmax$

    For $i = 1, \dots, I$

        Given the current values of the competitors' bid prices, i.e.
        $\left(b_u^{\mathcal{U}}, b_u^{\mathcal{U},\uparrow}, b_u^{\mathcal{U},\downarrow}\right)_k$, $u \in \mathcal{U}_1 \cup \cdots \cup \mathcal{U}_{i-1}$, and $\left(b_n^{\mathcal{N},\downarrow}\right)_k$, $n \in \mathcal{N}_1 \cup \cdots \cup \mathcal{N}_{i-1}$
        $\left(b_u^{\mathcal{U}}, b_u^{\mathcal{U},\uparrow}, b_u^{\mathcal{U},\downarrow}\right)_{k-1}$, $u \in \mathcal{U}_{i+1} \cup \cdots \cup \mathcal{U}_I$, and $\left(b_n^{\mathcal{N},\downarrow}\right)_{k-1}$, $n \in \mathcal{N}_{i+1} \cup \cdots \cup \mathcal{N}_I$
        compute optimal bid prices for Aggregator $i$:
        $\left(b_u^{\mathcal{U}}, b_u^{\mathcal{U},\uparrow}, b_u^{\mathcal{U},\downarrow}\right)_k$, $u \in \mathcal{U}_i$, and $\left(b_n^{\mathcal{N},\downarrow}\right)_k$, $n \in \mathcal{N}_i$      (*)

        If optimal bid prices (*) differ from those computed at iteration $k-1$, set flag $\varphi_i = 1$,
            otherwise set $\varphi_i = 0$.

    If $\varphi_i = 0$, for all $i \in I$, STOP,   as none of the Aggregators has unilaterally deviated
                                                    from the solution computed at the previous iteration.
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- Alternative coordination schemes B and C
- Comparison on a small scale network test

Constraints for modelling the ASM in Coordination Schemes A and B

- Constraints specific to Coordination Scheme A (a unique ASM for all the system)

$g_{u,s}^{\uparrow}$, $g_{u,s}^{\downarrow}$, $u \in \mathcal{U}$, and $d_{n,s}^{\downarrow}$, $n \in \mathcal{N}$ determined by the optimality conditions of the unique ASM

(all flexibility resources in the system)

- Constraints specific to Coordination Scheme B (each network has its own ASM)

$g_{u,s}^{\uparrow}$, $g_{u,s}^{\downarrow}$, $u \in \mathcal{U}^{\mathcal{D}_k}$, and $d_{n,s}^{\downarrow}$, $n \in \mathcal{N}^{\mathcal{D}_k}$, determined by the optimality conditions of the **ASM in distribution** network $\mathcal{D}_k$, $1 \leq k \leq K$

(flexibility resources in $\mathcal{D}_k$ only)

$g_{u,s}^{\uparrow}$, $g_{u,s}^{\downarrow}$, $u \in \mathcal{U}^{\mathcal{T}}$, and $d_{n,s}^{\downarrow}$, $n \in \mathcal{N}^{\mathcal{T}}$, determined by the optimality conditions of the **ASM in transmission network** $\mathcal{T}$

(flexibility resources in $\mathcal{T}$ only)

Constraints for modelling the ASM in Coordination Scheme C

flexibility resources in $\mathcal{D}_k$	$u \in \mathcal{U}^{\mathcal{D}_k}$		$n \in \mathcal{N}^{\mathcal{D}_k}$
	up-regulation	down-regulation	load curtailment
participate in $\mathcal{D}_k$-ASM	$b_{u,a}^{\mathcal{U},\mathcal{D}_k,\uparrow}$	$b_{u,a}^{\mathcal{U},\mathcal{D}_k,\downarrow}$	$b_{n,a}^{\mathcal{N},\mathcal{D},\downarrow}$
and in $\mathcal{T}$-ASM	$b_{u,a}^{\mathcal{U},\mathcal{T},\uparrow}$	$b_{u,a}^{\mathcal{U},\mathcal{T},\downarrow}$	$b_{n,a}^{\mathcal{N},\mathcal{T},\downarrow}$

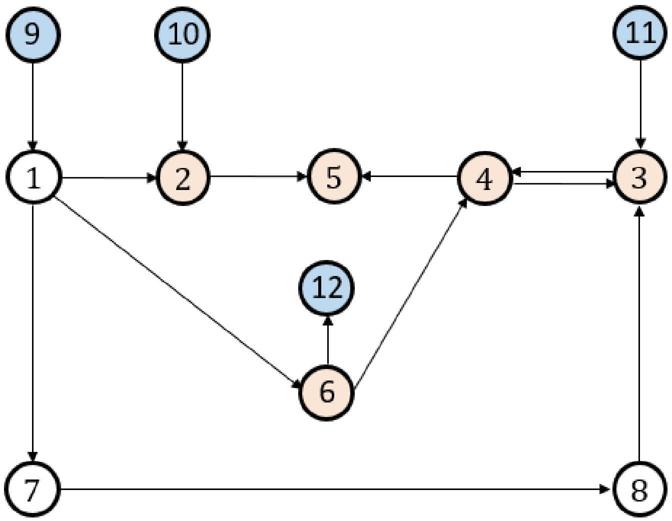
flexibility resources in $\mathcal{T}$	$u \in \mathcal{U}^{\mathcal{T}}$		$n \in \mathcal{N}^{\mathcal{T}}$
	up-regulation	down-regulation	load curtailment
participate in $\mathcal{T}$-ASM	$b_{u,a}^{\mathcal{U},\mathcal{T},\uparrow}$	$b_{u,a}^{\mathcal{U},\mathcal{T},\downarrow}$	$b_{n,a}^{\mathcal{N},\mathcal{T},\downarrow}$

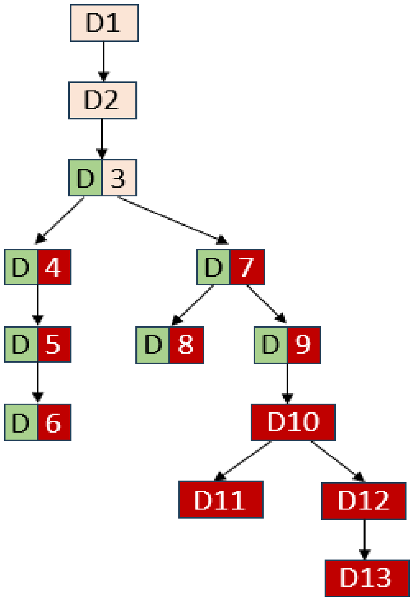
1) $g_{u,s}^{\mathcal{D},\uparrow}$, $g_{u,s}^{\mathcal{D},\downarrow}$, $u \in \mathcal{U}^{\mathcal{D}}$, and $d_{n,s}^{\mathcal{D},\downarrow}$, $n \in \mathcal{N}^{\mathcal{D}}$, determined by the optimality conditions of the **ASM in distribution** network $\mathcal{D}_k$, $1 \leq k \leq K$

(flexibility resources in $\mathcal{D}_k$ only)

2) $g_{u,s}^{\mathcal{T},\uparrow}$, $g_{u,s}^{\mathcal{T},\downarrow}$, $u \in \mathcal{U}$, and $d_{n,s}^{\mathcal{T},\downarrow}$, $n \in \mathcal{N}$, determined by the optimality conditions of the **ASM in transmission network** $\mathcal{T}$

(all flexibility resources in the system)





CIGRE transmission network with

- ➢ 12 nodes
- ➢ 14 power lines
- ➢ 4 programmable generators 🔵
- ➢ 5 flexible loads ●
- ➢ **3 Aggregators**

3 CIGRE distribution networks, each one with

- ➢ 13 nodes
- ➢ 12 power lines
- ➢ 7 RES power plants 🟩
- ➢ 3 flexible loads ▭
- ➢ 10 non- flexible loads 🟥
- ➢ **2 Aggregators**

Bidding prices alternatives considered by Aggregators operating in transmission $\mathcal{T}$

		$B_{u,1}^{\mathcal{U}}$	$B_{u,2}^{\mathcal{U}}$	$B_{u,3}^{\mathcal{U}}$	$B_{u,1}^{\mathcal{U},\uparrow}$	$B_{u,2}^{\mathcal{U},\uparrow}$	$B_{u,3}^{\mathcal{U},\uparrow}$	$B_{u,1}^{\mathcal{U},\downarrow}$	$B_{u,2}^{\mathcal{U},\downarrow}$	$B_{u,3}^{\mathcal{U},\downarrow}$	$B_{n,1}^{\mathcal{N},\downarrow}$	$B_{n,2}^{\mathcal{N},\downarrow}$	$B_{n,3}^{\mathcal{N},\downarrow}$
		1.1 C_u	1.2 C_u	1.3 C_u	1.1 $C_u^{\uparrow}$	1.3 $C_u^{\uparrow}$	1.5 $C_u^{\uparrow}$	0.9 $C_u^{\downarrow}$	0.8 $C_u^{\downarrow}$	0.5 $C_u^{\downarrow}$			
$A_1^{\mathcal{T}}$	U_1	96.80	105.60	114.40	145.20	171.60	198.00	39.60	30.80	22.00			
	U_2	79.20	86.40	93.60	118.80	140.40	162.00	32.40	25.20	18.00			
	N_4										93.53	140.30	224.48
$A_2^{\mathcal{T}}$	U_3	100.10	109.20	118.30	150.15	177.45	204.75	40.95	31.85	22.75			
	U_4	78.10	85.20	92.30	117.15	138.45	159.75	31.95	24.85	17.75			
	N_6										94.22	141.34	226.14
$A_3^{\mathcal{T}}$	N_2										95.00	142.50	228.00
	N_3										98.79	148.18	237.09
	N_5										95.74	143.61	229.77

Bidding prices alternatives considered by Aggregators operating in distribution networks $\mathcal{D}_k$

		$B^{\mathcal{U}}_{u,1}$	$B^{\mathcal{U}}_{u,2}$	$B^{\mathcal{U}}_{u,3}$	$B^{\mathcal{U},\uparrow}_{u,1}$	$B^{\mathcal{U},\uparrow}_{u,2}$	$B^{\mathcal{U},\uparrow}_{u,3}$	$B^{\mathcal{U},\downarrow}_{u,1}$	$B^{\mathcal{U},\downarrow}_{u,2}$	$B^{\mathcal{U},\downarrow}_{u,3}$	$B^{\mathcal{N},\downarrow}_{n,1}$	$B^{\mathcal{N},\downarrow}_{n,2}$	$B^{\mathcal{N},\downarrow}_{n,3}$
		1.1 C_u	1.2 C_u	1.3 C_u	1.1 $C^{\uparrow}_u$	1.3 $C^{\uparrow}_u$	1.5 $C^{\uparrow}_u$	0.9 $C^{\downarrow}_u$	0.8 $C^{\downarrow}_u$	0.5 $C^{\downarrow}_u$			
$A^{\mathcal{D}_1}_1$	U_5	93.50	102.00	110.50	140.25	165.75	191.25	38.25	29.75	21.25			
	N_{14}										99.00	148.50	237.60
$A^{\mathcal{D}_1}_2$	U_6	88.00	96.00	104.00	132.00	156.00	180.00	36.00	28.00	20.00			
	N_{13}										97.47	146.21	233.94
	N_{15}										96.35	144.53	231.25
$A^{\mathcal{D}_2}_1$	U_7	82.50	90.00	97.50	123.75	146.25	168.75	33.75	26.25	18.75			
	N_{28}										94.05	141.08	225.72
$A^{\mathcal{D}_2}_2$	U_8	94.60	103.20	111.80	141.90	167.70	193.50	38.70	30.10	21.50			
	N_{27}										92.60	138.90	222.24
	N_{29}										91.54	137.31	219.69
$A^{\mathcal{D}_3}_1$	U_9	90.20	82.00	106.60	135.30	159.90	184.50	36.90	28.70	20.50			
	N_{42}										99.10	148.65	237.84
$A^{\mathcal{D}_3}_2$	U_{10}	80.30	73.00	94.90	120.45	142.35	164.25	32.85	25.55	18.25			
	N_{41}										97.57	146.36	234.18
	N_{43}										100.01	150.02	240.02

Coordination scheme A: bid prices selected in transmission

		$B_{u,1}^{\mathcal{U}}$	$B_{u,2}^{\mathcal{U}}$	$B_{u,3}^{\mathcal{U}}$	$B_{u,1}^{\mathcal{U},\uparrow}$	$B_{u,2}^{\mathcal{U},\uparrow}$	$B_{u,3}^{\mathcal{U},\uparrow}$	$B_{u,1}^{\mathcal{U},\downarrow}$	$B_{u,2}^{\mathcal{U},\downarrow}$	$B_{u,3}^{\mathcal{U},\downarrow}$	$B_{n,1}^{\mathcal{N},\downarrow}$	$B_{n,2}^{\mathcal{N},\downarrow}$	$B_{n,3}^{\mathcal{N},\downarrow}$
		$1.1\ C_u$	$1.2\ C_u$	$1.3\ C_u$	$1.1\ C_u^{\uparrow}$	$1.3\ C_u^{\uparrow}$	$1.5\ C_u^{\uparrow}$	$0.9\ C_u^{\downarrow}$	$0.8\ C_u^{\downarrow}$	$0.5\ C_u^{\downarrow}$			
$A_1^{\mathcal{T}}$	U_1	96.80	105.60	114.40	145.20	171.60	198.00	39.60	30.80	22.00			
	U_2	79.20	86.40	93.60	~~118.80~~	~~140.40~~	~~162.00~~	32.40	25.20	18.00			
	N_4										93.53	140.30	224.48
$A_2^{\mathcal{T}}$	U_3	100.10	109.20	118.30	150.15	177.45	204.75	40.95	31.85	22.75			
	U_4	78.10	85.20	92.30	~~117.15~~	~~138.45~~	~~159.75~~	31.95	24.85	17.75			
	N_6										94.22	141.34	226.14
$A_3^{\mathcal{T}}$	N_2										95.00	142.50	228.00
	N_3										98.79	148.18	237.09
	N_5										95.74	143.61	229.77

× U_2 and U_4 do not submit the up-regulation bid, as they are fully dispatched on DAM

Coordination scheme A: bid prices selected in distribution

		$B^{\mathcal{U}}_{u,1}$	$B^{\mathcal{U}}_{u,2}$	$B^{\mathcal{U}}_{u,3}$	$B^{\mathcal{U},\uparrow}_{u,1}$	$B^{\mathcal{U},\uparrow}_{u,2}$	$B^{\mathcal{U},\uparrow}_{u,3}$	$B^{\mathcal{U},\downarrow}_{u,1}$	$B^{\mathcal{U},\downarrow}_{u,2}$	$B^{\mathcal{U},\downarrow}_{u,3}$	$B^{\mathcal{N},\downarrow}_{n,1}$	$B^{\mathcal{N},\downarrow}_{n,2}$	$B^{\mathcal{N},\downarrow}_{n,3}$
		1.1 C_u	1.2 C_u	1.3 C_u	1.1 $C^{\uparrow}_u$	1.3 $C^{\uparrow}_u$	1.5 $C^{\uparrow}_u$	0.9 $C^{\downarrow}_u$	0.8 $C^{\downarrow}_u$	0.5 $C^{\downarrow}_u$			
$A^{\mathcal{D}_1}_1$	U_5	93.50	102.00	110.50	~~140.25~~	~~165.75~~	~~191.25~~	38.25	29.75	21.25			
	N_{14}										99.00	148.50	237.60
$A^{\mathcal{D}_1}_2$	U_6	88.00	96.00	104.00	~~132.00~~	~~156.00~~	~~180.00~~	36.00	28.00	20.00			
	N_{13}										97.47	146.21	233.94
	N_{15}										96.35	144.53	231.25
$A^{\mathcal{D}_2}_1$	U_7	82.50	90.00	97.50	~~123.75~~	~~146.25~~	~~168.75~~	33.75	26.25	18.75			
	N_{28}										94.05	141.08	225.72
$A^{\mathcal{D}_2}_2$	U_8	94.60	103.20	111.80	~~141.90~~	~~167.70~~	~~193.50~~	38.70	30.10	21.50			
	N_{27}										92.60	138.90	222.24
	N_{29}										91.54	137.31	219.69
$A^{\mathcal{D}_3}_1$	U_9	90.20	82.00	106.60	~~135.30~~	~~159.90~~	~~184.50~~	36.90	28.70	20.50			
	N_{42}										99.10	148.65	237.84
$A^{\mathcal{D}_3}_2$	U_{10}	80.30	73.00	94.90	~~120.45~~	~~142.35~~	~~164.25~~	32.85	25.55	18.25			
	N_{41}										97.57	146.36	234.18
	N_{43}										100.01	150.02	240.02

Coordination scheme B: bid prices selected in transmission

		$B_{u,1}^{\mathcal{U}}$	$B_{u,2}^{\mathcal{U}}$	$B_{u,3}^{\mathcal{U}}$	$B_{u,1}^{\mathcal{U},\uparrow}$	$B_{u,2}^{\mathcal{U},\uparrow}$	$B_{u,3}^{\mathcal{U},\uparrow}$	$B_{u,1}^{\mathcal{U},\downarrow}$	$B_{u,2}^{\mathcal{U},\downarrow}$	$B_{u,3}^{\mathcal{U},\downarrow}$	$B_{n,1}^{\mathcal{N},\downarrow}$	$B_{n,2}^{\mathcal{N},\downarrow}$	$B_{n,3}^{\mathcal{N},\downarrow}$
		$1.1\ C_u$	$1.2\ C_u$	$1.3\ C_u$	$1.1\ C_u^{\uparrow}$	$1.3\ C_u^{\uparrow}$	$1.5\ C_u^{\uparrow}$	$0.9\ C_u^{\downarrow}$	$0.8\ C_u^{\downarrow}$	$0.5\ C_u^{\downarrow}$			
$A_1^{\mathcal{T}}$	U_1	96.80	105.60	114.40	145.20	171.60	198.00	39.60	30.80	22.00			
	U_2	79.20	86.40	93.60	~~118.80~~	~~140.40~~	~~162.00~~	32.40	25.20	18.00			
	N_4										93.53	140.30	224.48
$A_2^{\mathcal{T}}$	U_3	100.10	109.20	118.30	150.15	177.45	204.75	40.95	31.85	22.75			
	U_4	78.10	85.20	92.30	~~117.15~~	~~138.45~~	~~159.75~~	31.95	24.85	17.75			
	N_6										94.22	141.34	226.14
$A_3^{\mathcal{T}}$	N_2										95.00	142.50	228.00
	N_3										98.79	148.18	237.09
	N_5										95.74	143.61	229.77

In transmission no differences with the price selections made in SCHEME A

Coordination scheme B: bid prices selected in distribution

in red the differences with SCHEME A

		$B^{\mathcal{U}}_{u,1}$	$B^{\mathcal{U}}_{u,2}$	$B^{\mathcal{U}}_{u,3}$	$B^{\mathcal{U},\uparrow}_{u,1}$	$B^{\mathcal{U},\uparrow}_{u,2}$	$B^{\mathcal{U},\uparrow}_{u,3}$	$B^{\mathcal{U},\downarrow}_{u,1}$	$B^{\mathcal{U},\downarrow}_{u,2}$	$B^{\mathcal{U},\downarrow}_{u,3}$	$B^{\mathcal{N},\downarrow}_{n,1}$	$B^{\mathcal{N},\downarrow}_{n,2}$	$B^{\mathcal{N},\downarrow}_{n,3}$
		1.1 C_u	1.2 C_u	1.3 C_u	1.1 $C^{\uparrow}_u$	1.3 $C^{\uparrow}_u$	1.5 $C^{\uparrow}_u$	0.9 $C^{\downarrow}_u$	0.8 $C^{\downarrow}_u$	0.5 $C^{\downarrow}_u$			
$A^{\mathcal{D}_1}_1$	U_5	93.50	102.00	110.50	~~140.25~~	~~165.75~~	~~191.25~~	38.25	29.75	21.25			
	N_{14}										99.00	148.50	237.60
$A^{\mathcal{D}_1}_2$	U_6	88.00	96.00	104.00	~~132.00~~	~~156.00~~	~~180.00~~	36.00	28.00	20.00			
	N_{13}										97.47	146.21	233.94
	N_{15}										96.35	144.53	231.25
$A^{\mathcal{D}_2}_1$	U_7	82.50	90.00	97.50	~~123.75~~	~~146.25~~	~~168.75~~	33.75	26.25	18.75			
	N_{28}										94.05	141.08	225.72
$A^{\mathcal{D}_2}_2$	U_8	94.60	103.20	111.80	~~141.90~~	~~167.70~~	~~193.50~~	38.70	30.10	21.50			
	N_{27}										92.60	138.90	222.24
	N_{29}										91.54	137.31	219.69
$A^{\mathcal{D}_3}_1$	U_9	90.20	82.00	106.60	~~135.30~~	~~159.90~~	~~184.50~~	36.90	28.70	20.50			
	N_{42}										99.10	148.65	237.84
$A^{\mathcal{D}_3}_2$	U_{10}	80.30	73.00	94.90	~~120.45~~	~~142.35~~	~~164.25~~	32.85	25.55	18.25			
	N_{41}										97.57	146.36	234.18
	N_{43}										100.01	150.02	240.02

Coordination scheme C: bid prices selected in transmission

		$B^{\mathcal{U}}_{u,1}$	$B^{\mathcal{U}}_{u,2}$	$B^{\mathcal{U}}_{u,3}$	$B^{\mathcal{U},\uparrow}_{u,1}$	$B^{\mathcal{U},\uparrow}_{u,2}$	$B^{\mathcal{U},\uparrow}_{u,3}$	$B^{\mathcal{U},\downarrow}_{u,1}$	$B^{\mathcal{U},\downarrow}_{u,2}$	$B^{\mathcal{U},\downarrow}_{u,3}$	$B^{\mathcal{N},\downarrow}_{n,1}$	$B^{\mathcal{N},\downarrow}_{n,2}$	$B^{\mathcal{N},\downarrow}_{n,3}$
		$1.1\ C_u$	$1.2\ C_u$	$1.3\ C_u$	$1.1\ C_u^{\uparrow}$	$1.3\ C_u^{\uparrow}$	$1.5\ C_u^{\uparrow}$	$0.9\ C_u^{\downarrow}$	$0.8\ C_u^{\downarrow}$	$0.5\ C_u^{\downarrow}$			
$A^{\mathcal{T}}_1$	U_1	96.80	105.60	114.40	145.20	171.60	198.00	39.60	30.80	22.00			
	U_2	79.20	86.40	93.60	~~118.80~~	~~140.40~~	~~162.00~~	32.40	25.20	18.00			
	N_4										93.53	140.30	224.48
$A^{\mathcal{T}}_2$	U_3	100.10	109.20	118.30	150.15	177.45	204.75	40.95	31.85	22.75			
	U_4	78.10	85.20	92.30	~~117.15~~	~~138.45~~	~~159.75~~	31.95	24.85	17.75			
	N_6										94.22	141.34	226.14
$A^{\mathcal{T}}_3$	N_2										95.00	142.50	228.00
	N_3										98.79	148.18	237.09
	N_5										95.74	143.61	229.77

In transmission no differences with the price selections made in SCHEME A

Coordination scheme C: bid prices selected in distribution

		$B^{\mathcal{U}}_{u,1}$	$B^{\mathcal{U}}_{u,2}$	$B^{\mathcal{U}}_{u,3}$	$B^{\mathcal{U},\uparrow}_{u,1}$	$B^{\mathcal{U},\uparrow}_{u,2}$	$B^{\mathcal{U},\uparrow}_{u,3}$	$B^{\mathcal{U},\downarrow}_{u,1}$	$B^{\mathcal{U},\downarrow}_{u,2}$	$B^{\mathcal{U},\downarrow}_{u,3}$	$B^{\mathcal{N},\downarrow}_{n,1}$	$B^{\mathcal{N},\downarrow}_{n,2}$	$B^{\mathcal{N},\downarrow}_{n,3}$
		$1.1\ C_u$	$1.2\ C_u$	$1.3\ C_u$	$1.1\ C_u^{\uparrow}$	$1.3\ C_u^{\uparrow}$	$1.5\ C_u^{\uparrow}$	$0.9\ C_u^{\downarrow}$	$0.8\ C_u^{\downarrow}$	$0.5\ C_u^{\downarrow}$			
$A_1^{\mathcal{D}_1}$	U_5	93.50	102.00	110.50	~~140.25~~	~~165.75~~	~~191.25~~	38.25	29.75	21.25			
	N_{14}										99.00	148.50	237.60
$A_2^{\mathcal{D}_1}$	U_6	88.00	96.00	104.00	~~132.00~~	~~156.00~~	~~180.00~~	36.00	28.00	20.00			
	N_{13}										97.47	146.21	233.94
	N_{15}										96.35	144.53	231.25
$A_1^{\mathcal{D}_2}$	U_7	82.50	90.00	97.50	~~123.75~~	~~146.25~~	~~168.75~~	33.75	26.25	18.75			
	N_{28}										94.05	141.08	225.72
$A_2^{\mathcal{D}_2}$	U_8	94.60	103.20	111.80	~~141.90~~	~~167.70~~	~~193.50~~	38.70	30.10	21.50			
	N_{27}										92.60	138.90	222.24
	N_{29}										91.54	137.31	219.69
$A_1^{\mathcal{D}_3}$	U_9	90.20	82.00	106.60	~~135.30~~	~~159.90~~	~~184.50~~	36.90	28.70	20.50			
	N_{42}										99.10	148.65	237.84
$A_2^{\mathcal{D}_3}$	U_{10}	80.30	73.00	94.90	~~120.45~~	~~142.35~~	~~164.25~~	32.85	25.55	18.25			
	N_{41}										97.57	146.36	234.18
	N_{43}										100.01	150.02	240.02

Scenarios with Positive imbalance:

- real-time net load > generation scheduled in DAM
- requires up-regulation and/or load curtailment

Scenarios with Negative imbalance:

- real-time net load < generation scheduled in DAM
- requires down-regulation and/or curtailment of RES power output

Imbalance scenarios [MWh]

Scenarios	Δ_s	$\Delta_s^{\mathcal{T}}$	$\Delta_s^{\mathcal{D}_1}$	$\Delta_s^{\mathcal{D}_2}$	$\Delta_s^{\mathcal{D}_3}$	Scheme A	Scheme B	Scheme C
s_1	129	99	9	6	15	23237.87	21227.42	26136.85
s_2	86	66	6	4	10	16934.08	15752.79	18952.68
s_3	43	33	3	2	2	10822.99	10375.93	11836.83
s_4	0	0	0	0	0	5003.63	5014.85	5003.63
s_5	−43	−33	−3	−2	−5	−445.83	724.10	1057.53
s_6	−86	−66	−6	−4	−10	−3371.33	−3338.82	−2888.56
s_7	−129	−99	−9	−6	−15	−5057.00	−5008.21	−5054.42
					Expected cost	6717.77	6390.01	7863.51