Impacts of Topology Control on Zonal Markets

Quentin Lété (UCLouvain)
Joint work with Anthony Papavasiliou

INFORMS Annual Meeting 2019
23 October 2019

Outline

Introduction

Models of zonal markets with transmission switching

An algorithmic approach to proactive switching

Conclusion

Introduction

Models of zonal markets with transmission switching

An algorithmic approach to proactive switching

Conclusion

Zonal electricity markets

- In Europe, the market is organized as a zonal market
  - Unique price per zone
  - Intra-zonal transmission constraints ignored
  - Transmission constraints defined at the zonal level
- Two models of market coupling in Europe :
  1. Available-Transfer-Capacity (ATC): Limit on the power exchanged between two zones
  2. Flow-Based (FBMC): Polyhedral constraints on zonal net injections which can capture constraints that the ATC model cannot
- FBMC went live in Central Western Europe (CWE) in May 2015
- Recent analysis (Aravena *et al*, 2018) shows that ATC and FBMC attain comparable performance and are outperformed by nodal pricing in terms of short-run operational efficiency
- Difference comes from inefficiency of zonal pricing in terms of day-ahead **unit commitment**

Transmission switching in zonal markets

- Transmission switching can significantly help with congestion management in zonal markets
- Questions:
  1. To what extent can transmission switching improve the efficiency of zonal markets?
  2. How does the resulting performance compare to nodal?

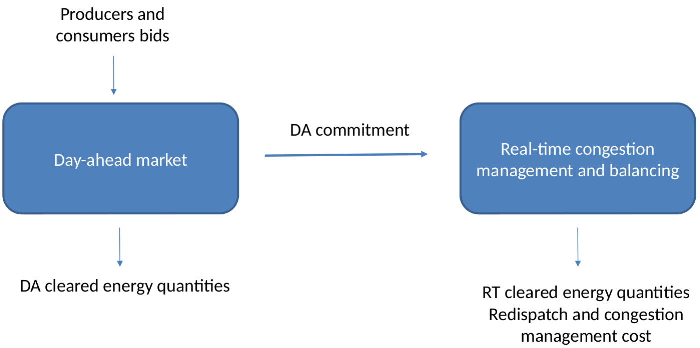
Introduction

Models of zonal markets with transmission switching

An algorithmic approach to proactive switching

Conclusion

Day-ahead and real-time model



Day-ahead market clearing with proactive switching

$$\min_{v\in[0,1],p,t} \sum_{g\in G} P_g Q_g v_g$$

$$\text{s.t.} \sum_{g\in G(z)} Q_g v_g - p_z = \sum_{n\in N(z)} Q_n \qquad \forall z \in Z$$

$$p \in \bigcap_{\|u\|_1\leq 1} \mathcal{P}_t(u)$$

- (P_g, Q_g) is the price quantity bid of generator g
- v_g is the acceptance of the bid of generator g
- p_z is the net position of zone z
- u is the generator and line contingency
- $\mathcal{P}$ is the acceptable set of net positions, which depends on the topology (t).

Algorithm for proactive switching

Idea

Write the problem as an Adaptive Robust Optimization problem with mixed integer recourse of the following form:

$$\min_{\mathbf{x}\in\mathbb{X}} \mathbf{cx} + \max_{\mathbf{u}\in\mathbb{U}} \min_{\mathbf{z},\mathbf{y}\in\mathbb{F}(\mathbf{u},\mathbf{x})} \mathbf{dy} + \mathbf{gz}$$

where

- $\mathbb{X} = \{\mathbf{x} \in \mathbb{R}_+^m \times \mathbb{Z}_+^m : A\mathbf{x} \geq b\}$
- $\mathbb{F}(u,x) = \{(\mathbf{z},\mathbf{y}) \in \mathbb{Z}_+^n \times \mathbb{R}_+^p : E(\mathbf{u})\mathbf{y} + G(\mathbf{u})\mathbf{z} \geq f(\mathbf{u}) - D(\mathbf{u})\mathbf{x}\}$
- $\mathbb{U}$ is a bounded binary set in the form of $\mathbb{U} = \{u \in \mathbb{B}_+^q : H\mathbf{u} \leq a\}$.

This generic formulation is similar to that of Zhao and Zeng

DA market clearing with N-1 and TS as an AROMIP

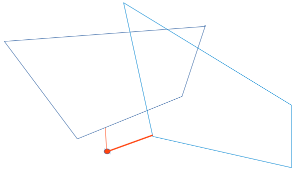
Three steps:

1. Rewrite the constraint $p \in \bigcap_{\|u\|_1 \leq 1} \mathcal{P}_t(u)$ as
$$d(p, \bigcap_{\|u\|_1 \leq 1} \mathcal{P}_t(u)) = 0$$
2. Move it in the objective
$$\min_{v \in [0,1], p, t} \sum_{g \in G} P_g Q_g v_g + \lambda^* \Big(d(p, \bigcap_{\|u\|_1 \leq 1} \mathcal{P}_t(u)) \Big)$$
$$\text{s.t.} \sum_{g \in G(z)} Q_g v_g - p_z = \sum_{n \in N(z)} Q_n \qquad \forall z \in Z \qquad (1)$$
3. Write the distance as an adversarial max-min problem :
$$d(p, \bigcap_{\|u\|_1 \leq 1} \mathcal{P}_t(u)) = \max_{u \in \mathbb{U}} \min_{\tilde{p}, t} \|p - \tilde{p}\|_1$$
$$\text{s.t. } \tilde{p} \in \mathcal{P}_t(u) \qquad (2)$$

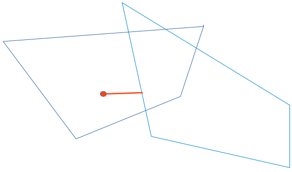
Distance to the set of net position

$$d(p, \bigcap_{\|u\|_1 \leq 1} \mathcal{P}_t(u)) = \max_{u \in \mathbb{U}} \min_{\tilde{p}, t} \|p - \tilde{p}\|_1$$
$$\text{s.t. } \tilde{p} \in \mathcal{P}_t(u)$$

If we are outside of the union :



If we are in the union :



$\rightarrow$ In both cases, define the distance to the **intersection** as the maximum of both single set distances

DA market clearing with N-1 and TS as an AROMIP

We obtain the same form as

$$\min_{\mathbf{x}\in\mathbb{X}} \mathbf{cx} + \max_{\mathbf{u}\in\mathbb{U}} \min_{\mathbf{z},\mathbf{y}\in\mathbb{F}(\mathbf{u},\mathbf{x})} \mathbf{dy} + \mathbf{gz}$$

with the following correspondence :

- $\mathbf{x} = (v, p)$: the dispatch and corresponding net position
- $\mathbb{X} = (1)$: link between dispatch and net position
- $\mathbf{y} = \tilde{p}$: closest point to p in the set of acceptable net positions
- $\mathbf{z} = t$: topology variables
- $\mathbb{F} = (2)$: set of acceptable net positions for $\tilde{p}$

How to solve the AROMIP?

Assuming we can solve the adversarial problem

$\rightarrow$ Use the column-and-constraint generation algorithm of Zhao and Zeng

1. Set $LB = -\infty$, $UB = +\infty$ and $k = 0$
2. Solve the following master problem:

$$\textbf{MP:} \min_{v,p,t,\eta} \sum_{g} Q_g P_g v_g + \lambda^* \eta$$

$$\text{s.t.} \sum_{g \in G(z)} Q_g v_g - p_z = \sum_{n \in N(z)} Q_n$$

$$\eta \geq |p^i - p|, \quad \forall i \in \{1, ..., k\}$$

$$p^i \in \mathcal{P}_{t^i}(u^i), \quad \forall i \in \{1, ..., k\}$$

Update $LB = \sum_g Q_g P_g v_g^* + \lambda^* \eta^*$. If $UB - LB < \epsilon$, terminate.

How to solve the AROMIP?

Let p^* be the optimal solution for variable p in **MP**

3. Call the oracle to solve subproblem $d(p^*, \bigcap_{\|u\|_1 \leq 1} \mathcal{P}_t(u))$ and update

$$UB = \min\left(UB, \sum_g Q_g P_g v_g^* + \lambda^* d(p^*, \bigcap_{\|u\|_1 \leq 1} \mathcal{P}_t(u))\right)$$

   If $UB - LB < \epsilon$, terminate.

4. Create variable p^i and add the following constraints:

$$\eta \geq |p^i - p|$$
$$p^i \in \mathcal{P}_{t^i}(u_i^*)$$

   where u_i^* is the optimal value of variable u in the subproblem.

How to solve the adversarial problem?

This problem reads as follows :

$$d(p, \bigcap_{\|u\|_1 \leq 1} \mathcal{P}_t(u)) = \max_{u \in \mathbb{U}} \min_{\tilde{p}, t} |p - \tilde{p}| \quad \text{s.t. } \tilde{p} \in \mathcal{P}_t(u)$$

Our idea

Take advantage of the interdiction game nature of our problem.

How to solve the adversarial problem ?

The problem can be rewritten as an interdiction problem :

$$\begin{aligned} \max_{u \in \mathbb{U}} \ \min_{\tilde{p}, t} \ & |p - \tilde{p}| \\ \text{s.t. } & (\tilde{p}, t) \in \mathcal{Q} \\ & t_l u_l = 0 \quad \forall l \in L \end{aligned}$$

where $\mathcal{Q}$ is defined as $\mathcal{P}_t(\mathbf{0})$ in the space of p and t.

Penalizing the last constraint, we can put it in the objective :

$$\begin{aligned} \min_{\tilde{p}, t} \ & |p - \tilde{p}| + \sum_{l \in L} \lambda_l t_l u_l^* \\ \text{s.t. } & (\tilde{p}, t) \in \mathcal{Q} \end{aligned}$$

Conclusion

- Recent studies raise questions about the **efficiency of current** market clearing **design in Europe**
- Lack of systematic studies on the **impacts of transmission switching** on these designs

- New **framework for modeling FBMC** with both proactive (day-ahead) as well as reactive (real-time) switching
- An **algorithm** to solve the market clearing problem with proactive switching

Thank you

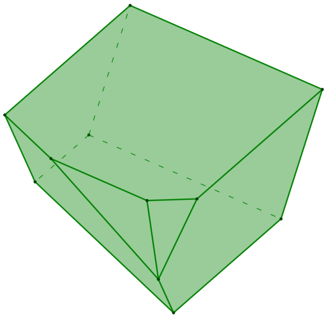
Contact :

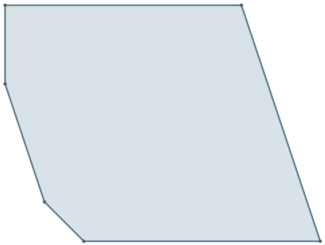
Quentin Lété, quentin.lete@uclouvain.be
Anthony Papavasiliou, anthony.papavasiliou@uclouvain.be

Acceptable set of net positions

$p \in \mathcal{P}$

space of nodal injections $\quad \rightarrow \quad$ space of zonal net positions

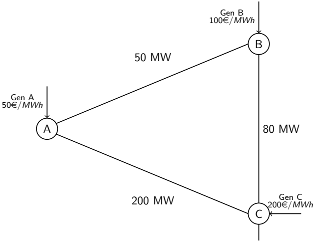




$$\mathcal{R} := \Big\{ r \in \mathbb{R}^{|N|} : r \text{ is feasible for the real network} \Big\}$$

$$\mathcal{P} := \Big\{ p \in \mathbb{R}^{|Z|} : \exists r \in \mathcal{R} : p_z = \sum_{n \in N(z)} r_n \;\; \forall z \in Z \Big\}$$

Acceptable set of net positions with switching

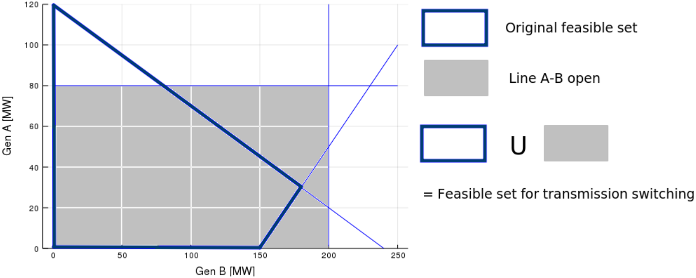


$p \in \mathcal{P}_t$

$$-50 \leq \frac{1}{3}\mathrm{GEN_A} - \frac{1}{3}\mathrm{GEN_B} \leq 50$$

$$-80 \leq \frac{1}{3}\mathrm{GEN_A} + \frac{2}{3}\mathrm{GEN_B} \leq 80$$

$$-200 \leq \frac{2}{3}\mathrm{GEN_A} + \frac{1}{3}\mathrm{GEN_B} \leq 200$$



→ solve on the union of polytopes

Acceptable set of net positions

- Put the two together

$$
\begin{aligned}
\mathcal{P}_t = \Big\{ & p \in \mathbb{R}^{|Z|} : \exists(\bar{v}, f, \theta, t) \in [0,1]^{|\mathcal{G}|} \times \mathbb{R}^{|L|} \times \mathbb{R}^{|N|} \times \{0,1\}^{|L|} : \\
& \sum_{g \in \mathcal{G}(z)} Q_g \bar{v}_g - p_z = \sum_{n \in N(z)} Q_n, \quad \forall z \in Z \\
& \sum_{g \in \mathcal{G}(n)} Q_g \bar{v}_g - \sum_{l \in L(n,\cdot)} f_l + \sum_{l \in L(\cdot,n)} f_l = Q_n, \quad \forall n \in N \\
& - t_l F_l \leq f_l \leq t_l F_l, \quad \forall l \in L \\
& f_l \leq B_l(\theta_{m(l)} - \theta_{n(l)}) + M(1 - t_l), \quad \forall l \in L \\
& f_l \geq B_l(\theta_{m(l)} - \theta_{n(l)}) - M(1 - t_l), \quad \forall l \in L \Big\}
\end{aligned}
$$

Case study: overview

- Simulation on 32 representative snapshots
- Benchmark against LMP-based market clearing
- We use generalized versions of the models presented that consider commitment (on-off) decisions for slow generators and reserves + N-1 security criterion
- Network: CWE area with
  - 346 slow generators with a total capacity of 154 GW
  - 301 fast thermal generators with a total capacity of 89 GW
  - 1312 renewable generators with a total capacity of 149 GW
  - 632 buses
  - 945 branches
- We use a switching budget of 6 lines
- All models are solved with JuMP 0.18.4 and Gurobi 8.0 on the Lemaitre3 cluster
- CPU time (all snapshots): 40.5 hours for cost-based redispatch with switching
  Median snapshot time: 51 min

Comparison of the cost of each TS option

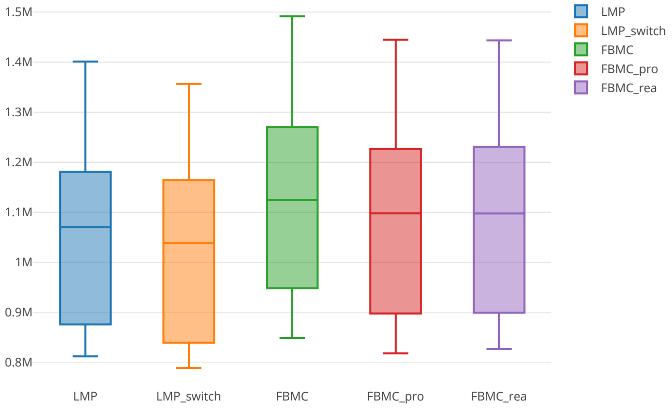


Figure 1: Total (DA+RT) hourly cost of the different policies on 32 snapshots of CWE.

Observations

1. Under min-cost redispatch, switching helps significantly in reducing the operating cost of the zonal design.
2. Incremental benefit of proactive switching in zonal is small.
3. Nodal market without switching still outperforms the zonal market with switching.
4. Benefits of switching in LMP and FBMC are comparable.

Numbers and ranking

Design option	Average cost [€]
1. LMP with switching	1 023 248
2. LMP without switching	1 054 240
3. Min-cost FBMC with proactive switching	1 084 281
4. Min-cost FBMC with reactive switching	1 085 511
5. Min-cost FBMC without switching	1 120 598

Table 1: Average hourly total cost of all design options.