Impacts of Transmission Switching on Zonal Markets

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Outline

Introduction

Models of zonal markets with transmission switching

An algorithm for proactive transmission switching

Case study: Impacts of transmission switching on CWE

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 - practices

Switching is much more widespread in Europe than in the US.

In Belgium (ELIA):

- Corrective measure for congestion management
- Decided in day-ahead
- Based on a list of candidate lines that can be switched ($\sim$ 50 lines)

At the Central Western European level:

- Coordinated by CORESO
- Based on grid state forecast and topological correction plans of each TSO

We are not aware of any implementation of transmission switching by means of optimization.

Transmission switching in zonal markets

- Transmission switching can significantly help with congestion management in zonal markets
- This argument depends on specific assumptions regarding balancing and congestion management coordination
- Questions:
  1. To what extent can transmission switching improve the efficiency of zonal markets?
  2. How does the resulting performance compare to nodal?
  3. How do these results depend on specific assumptions regarding balancing and congestion management practices?

Literature

Modeling

- [Fisher et al., 2008],[Hedman et al., 2010]: transmission switching can have a significant impact on operational cost.
- [Han and Papavasiliou, 2015]: Simplified model of European market with TS.
- [Aravena et al., 2018]: New modeling framework for comparing different market designs.

Algorithmic

- [Street et al., 2014]: Formulate N-1 market clearing as Adaptive Robust Optimization (ARO) problem using a Benders-like algorithm.
- [Zhao and Zeng, 2012]: Exact algorithm for solving ARO with mixed-integer recourse.

Contributions

Modeling

1. Model of a zonal market that accounts for transmission switching at both the day-ahead and the real-time stages.
2. Detailed analysis of various approaches to congestion management.

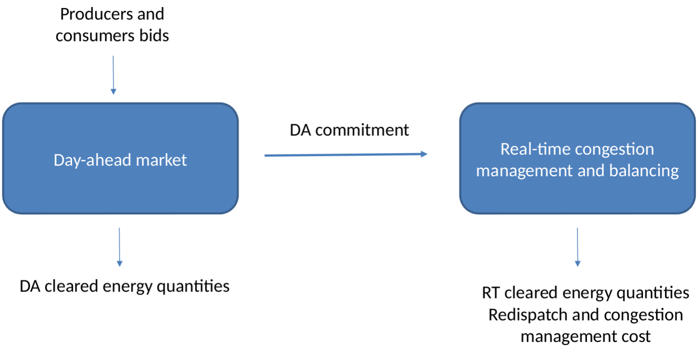
Computational

3. Formulate a zonal (flow-based) day-ahead market clearing model with switching as an adaptive robust optimization problem.

Policy

4. Simulation of each market design option on a detailed instance of the CWE network.
5. Discussion of the relative performance of each policy.

Day-ahead and real-time model



Overview of zonal market

- Two-stage model: Day-ahead market clearing + real-time congestion management and balancing.
- Day ahead:
  - Participants submit price-quantity bids
  - Market cleared to maximize welfare while respecting net position constraints which are described by a **zonal flow-based polytope**
  - Account for day-ahead clearing of reserve capacity
- Real time:
  - Using nodal constraints, TSOs find a new dispatch that is feasible for the grid. Inc-dec payments are cost-based.

Day-ahead market clearing with proactive switching

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

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

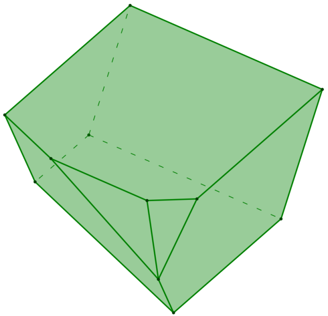
$$p \in \mathcal{P}_t$$

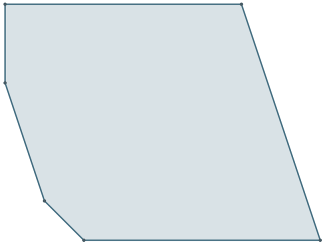
The acceptable set of net positions depends on the topology.

Acceptable set of net positions

$$p \in \mathcal{P}$$

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

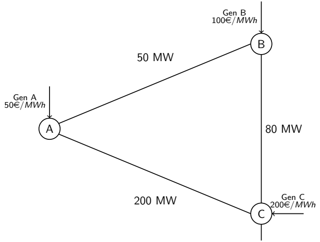




$$\mathcal{R} := \Big\{ r \in \mathbb{R}^{|N|} : r \text{ is feasible for the real network} \Big\}$$

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

Acceptable set of net positions with switching

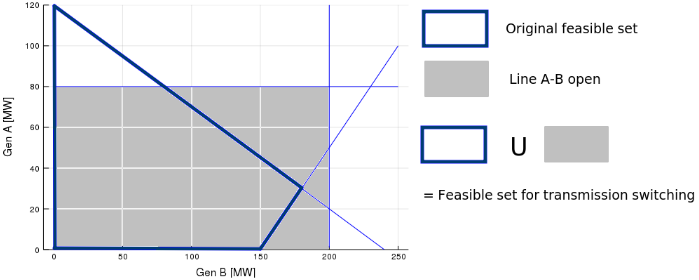


$p \in \mathcal{P}_t$

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

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

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



→ solve on the union of polytopes

Acceptable set of net positions

- Put the two together

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

DA market with TS and N-1 security criterion

- Security criterion: the system should be able to supply all demand for any outage of generating units or transmission lines
- Let $\mathcal{P}_t(u)$ be the feasible set of net positions under contingency $u \in \{0, 1\}^{|G|+|L|}$
- Constraint on acceptable net positions becomes:

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

Real-time redispatch

Goal

Find a new dispatch that is feasible with the nodal grid

No obvious way of how to model the current practice.

We propose three variants:

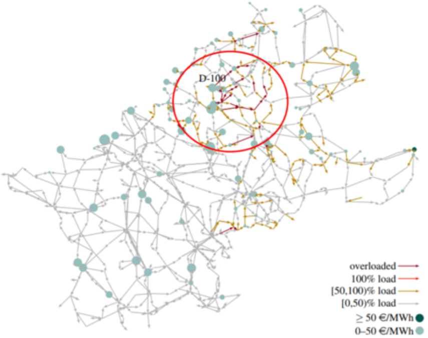
1. Cost-based redispatch
2. Volume-based redispatch
3. A heuristic based on the PTDF matrix

Poor unit commitment as a source of inefficiency

- Zonal models can result in **infeasible** power flows (e.g. starting up cheap coal)

- Power flows can be made feasible in real time, but it is costly, e.g.
  - reduce production of coal
  - start up combined cycle gas turbines

=> **operating costs that could be avoided**



Source: [Aravena, 2017]

Cost-based redispatch

Goal

Minimize the **cost** while respecting the constraints of the nodal grid

$$\begin{aligned}
\min_{\substack{v\in[0,1],f,\theta\\ t\in\{0,1\}}} \sum_{g\in G} P_g Q_g v_g & \\
\text{s.t.} \quad \sum_{g\in G(n)} Q_g v_g - \sum_{l\in L(n,\cdot)} f_l + \sum_{l\in L(\cdot,n)} f_l = Q_n, & \quad n \in N \\
-F_l t_l \le f_l \le F_l t_l, & \quad \forall l \in L \\
f_l \le B_l(\theta_{m(l)} - \theta_{n(l)}) + M(1 - t_l), & \quad \forall l \in L \\
f_l \ge B_l(\theta_{m(l)} - \theta_{n(l)}) - M(1 - t_l), & \quad \forall l \in L
\end{aligned}$$

Volume-based redispatch

Goal

Minimize the change in **volume** while respecting the constraints of the nodal grid

$$\min_{\substack{v\in[0,1],f,\theta \\ t\in\{0,1\}}} \sum_{g\in G} Q_g |v_g - v_g^{\text{DA}}|$$

$$\begin{aligned}
\text{s.t.} \quad & \sum_{g\in G(n)} Q_g v_g - \sum_{l\in L(n,\cdot)} f_l + \sum_{l\in L(\cdot,n)} f_l = Q_n, \quad n \in N \\
& -F_l t_l \leq f_l \leq F_l t_l, \quad \forall l \in L \\
& f_l \leq B_l(\theta_{m(l)} - \theta_{n(l)}) + M(1 - t_l), \quad \forall l \in L \\
& f_l \geq B_l(\theta_{m(l)} - \theta_{n(l)}) - M(1 - t_l), \quad \forall l \in L
\end{aligned}$$

where v_g^{DA} is a parameter corresponding to the dispatch obtained in day-ahead.

PTDF-based heuristic

Idea

Loop on the generators ordered by PTDF to relieve congestion

Algorithm 1: RCH (Remove Congestion Heuristic)

Input: initial dispatch v

Output: new dispatch that respects network constraints

let L_{cong} be the set of congested lines sorted by congestion magnitude

while $L_{cong} \neq \emptyset$ **do**

  for *every* $l \in L_{cong}$ **do**

    let N_{sorted} be the set of nodes sorted w.r.t. $\text{PTDF}_{l,n}$

    for $n \in N_{sorted}$ *until* $f_l \geq F_l$ **do**

      for $g \in G(n)$ *until* $f_l \geq F_l$ **do**

        $v_g = \max\{v_g - \frac{(f_l - F_l)}{\text{PTDF}_{l,n}}, 0\}$

      restore power balance

  update L_{cong}

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Algorithm for proactive switching

- Proactive switching: co-optimize the day-ahead generation schedule and network topology

Goal

Present an algorithm for solving the day-ahead zonal market clearing under N-1 robustness with proactive switching

This problem can be written as :

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

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

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

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 [Zhao and Zeng, 2012]

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

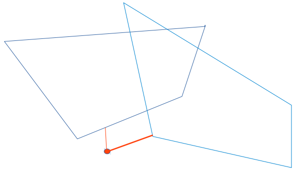
Three steps:

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 :
$$d(p, \bigcap_{\|u\|_1 \leq 1} \mathcal{P}_t(u)) = \max_{u \in \mathbb{U}} \min_{\tilde{p}, t} \|p - \tilde{p}\|_1$$
$$\text{s.t. } \tilde{p} \in \mathcal{P}_t(u) \qquad (2)$$

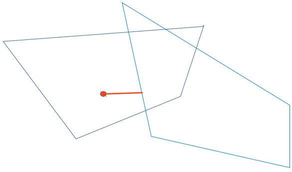
Distance to the set of net position

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

If we are outside of the union :



If we are in the union :



→ 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

→ 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:

$$
\begin{aligned}
\textbf{MP:} \quad \min_{v,p,t,\eta} & \sum_{g} Q_g P_g v_g + \lambda^* \eta \\
\text{s.t.} \quad & \sum_{g \in G(z)} Q_g v_g - p_z = \sum_{n \in N(z)} Q_n \\
& \eta \geq |p^i - p|, \qquad \forall i \in \{1, ..., k\} \\
& p^i \in \mathcal{P}_{t^i}(u^i), \qquad \forall i \in \{1, ..., k\}
\end{aligned}
$$

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.

Case study: overview

- Simulation on 32 representative snapshots of 7 zonal options
- 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
- 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

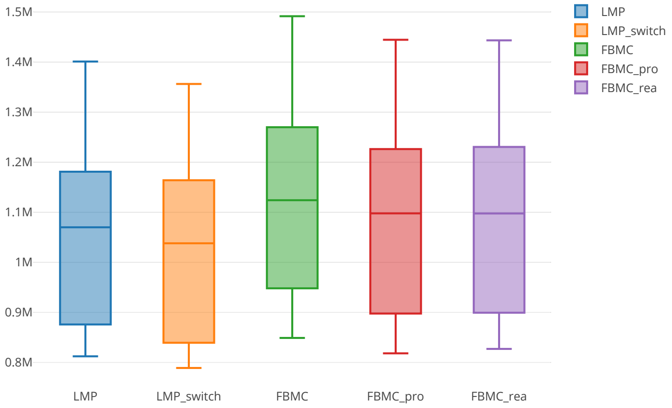


Figure 1: Total (DA+RT) hourly cost of the different policies on 32 snapshots of CWE.

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.

Comparison of redispatch methods

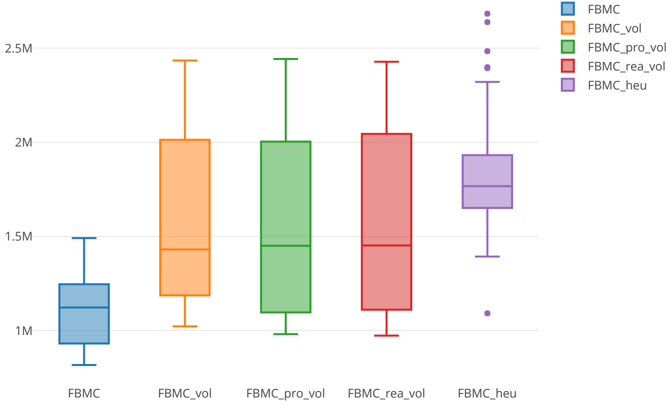


Figure 2: Total (DA+RT) hourly cost of the different redispatch methods on 32 snapshots of CWE.

Observations (2)

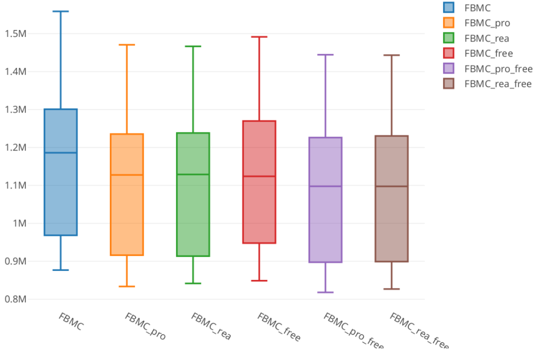
5. Assumptions about how balancing is performed have a very significant impact on the analysis:
   - Cost-based perfect coordination is the golden standard;
   - a PTDF-based heuristic method performs very poorly;
   - volume-based redispatch is enveloped by the two others.
6. The redispatch method used has a much more important influence on the cost than switching.
7. The benefits of switching in the case of volume-based redispatch are small.

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
6. Min-volume FBMC with reactive switching	1 595 089
7. Min-volume FBMC with proactive switching	1 596 371
8. Min-volume FBMC without switching	1 599 650
9. PTDF-based heuristic FBMC	1 852 580

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

Influence of fixing the net positions in redispatch



Cost increase of fixing the redispatch:

- No switching: $\frac{\text{FBMC}-\text{FBMC\_free}}{\text{FBMC\_free}} = 3.9\%$
- Proactive switching: $\frac{\text{FBMC\_pro}-\text{FBMC\_pro\_free}}{\text{FBMC\_pro\_free}} = 2.1\%$
- Reactive switching: $\frac{\text{FBMC\_rea}-\text{FBMC\_rea\_free}}{\text{FBMC\_rea\_free}} = 1.9\%$

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Conclusion

- New framework for modeling FBMC with both proactive (day-ahead) as well as reactive (real-time) switching
- Exact algorithm for clearing a zonal day-ahead market with switching and N-1 robustness

- Proactive switching improves FBMC operational costs significantly
- LMP still outperforms zonal design significantly
- Assumptions about the redispatch method have a very significant influence on cost

Future research questions

- Compare fixing the switching budget with other heuristics
- Understand pricing implications of zonal design and switching

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Thank you

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