Impacts of Transmission Switching in Zonal Electricity Markets - Part II

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***Abstract*—In this paper, we present a two-stage model of zonal electricity markets with day-ahead market clearing and real-time re-dispatch and balancing that accounts for transmission line switching at both stages. We show how the day-ahead problem with switching can be formulated as an adaptive robust optimization problem with mixed integer recourse and present a new algorithm for solving the adversarial max-min problem that obeys the structure of an interdiction game. We apply the model on a realistic instance of the Central Western European system and comment on the impacts of both proactive and reactive transmission switching on the operating costs of the system.**

Part I presents day-ahead models of a short-term zonal electricity market with switching, and describes our algorithmic approach for solving these models efficiently.

Part II describes variants of the real-time model, and presents the results of our case study on the Central Western European market.

***Index Terms*—Transmission switching, Zonal electricity market, Robust optimization**

I. Introduction

European countries have engaged in an ambitious plan for integrating renewable energy in electric power systems. The objective of the European Commission is to achieve a climate neutral economy by 2050 [1] and the large-scale integration of renewable resources is one of the means for achieving this goal.

The European zonal market design implies that the dispatch which is obtained in day-ahead market clearing does not necessarily satisfy network constraints. This, in turn, implies that real-time operations are separated into two distinct but closely related processes: *re-dispatch* and *balancing.*

Re-dispatch, which is referred to interchangeably as *congestion management*, is the act of increasing or decreasing the set-point of resources that can be adjusted near real time in order to relieve transmission line overloading. Such re-dispatching may be required, even if day-ahead forecasts anticipate perfectly the level of demand and renewable production in the system, due to the fact that zonal market clearing models may violate network constraints.

On the other hand, balancing refers to the action of adjusting resources in real time in order to exactly match supply and demand. Balancing actions are typically in response to the realization of renewable supply or load forecast errors, or due to the failure of generators and/or transmission components. We refer to re-dispatch in the present article as a means of coping with the violation of transmission constraints due to a zonal representation of the grid, even if the real-time realization of renewable supply unfolds exactly as forecast in the day ahead. In US operations, re-dispatch and balancing are effectively performed simultaneously, by means of a transmission-constrained economic dispatch model. In Europe, the two processes are considered separately, although this separation is largely artificial when reasoning in terms of an integrated optimization of energy and transmission capacity allocation.

A. Motivation of our work

The integration of renewable resources increases the need for real-time corrections, both in order to cope with the unpredictable fluctuations of renewable supply, but also in order to relieve unpredictable congestion patterns. This explains, to a certain extent, the recently observed increase in the cost of real-time operations in Europe. For instance, the cost of re-dispatch rose to €1 billion in 2017 in Germany alone [2]. It is largely acknowledged that transmission switching is one of the solutions that could contribute towards reducing these re-dispatch and balancing costs significantly, see [3] and references therein. The goal of this paper is to understand the potential impacts of transmission switching on the total (day-ahead and real-time) cost of operating the system, by considering a realistic simulation of the Central Western European system. As this assessment depends on specific assumptions regarding the execution of day-ahead and real-time operations, we proceed to a sensitivity analysis of the results with respect to these assumptions. This sensitivity analysis should enable the identification of the most important factors that influence the total cost and with that orientate future research and developments for the efficiency of short-term electricity operations in Europe.

B. Related literature

Modeling the real-time operation of the European market requires a careful identification of the following

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aspects of system operation: (i) the level of coordination of national Transmission System Operators (TSO) and (ii) the actual method used by TSOs for identifying re-dispatch and balancing actions.

TSO coordination. The importance of TSO coordination on the efficiency of power system operations is well documented in the literature. In 2005, Marinescu et al. [4] already highlighted and assessed the potential benefits of coordinated re-dispatch measures. Neuhoff et al. [5] highlight the challenges of congestion management in Europe and propose a set of criteria for assessing the different congestion management options. One of the criteria they identify is the transparency of congestion management methods that would allow effective cooperation between TSOs. Kunz and Zerrahn [6] simulate the implementation of different re-dispatch methods on an instance of the Central Eastern Europe system and identify that a perfectly coordinated re-dispatch could decrease re-dispatch cost by up to 80% compared to the case of uncoordinated re-dispatch. European TSOs acknowledge the importance of coordination in real time, as can be seen by the recent initiatives for integrated balancing markets. These initiatives include the creation of platforms for activating secondary (PICASSO[1]) and tertiary (MARI[2]) reserve activation by accounting for international transmission constraints through transportation-based zonal models [7].

In this paper, we follow this evolution of integrating balancing among European countries by assuming that TSOs coordinate perfectly in real time. This allows us to isolate the inefficiencies that are due to the zonal day-ahead model from the inefficiencies that are due to an imperfect real-time model. This assumption is then relaxed in section VI, in order to quantify the benefits of integrated balancing.

Methods for identifying re-dispatch and balancing measures. Most studies in the literature assume that a cost-minimizing re-dispatch and balancing model is applied real time. This is the case, for instance, in the aforementioned studies, but also in a number of recent publications that focus on modeling the short-term European electricity market [3], [8], [9], [10]. In order to understand whether this assumption is in line with current practices and European legislation, it is important to address separately the question of the objective of TSOs when performing re-dispatch and when performing balancing.

a) Re-dispatch: The Clean Energy Package (CEP) of the European Commission [11] establishes several principles for re-dispatching, as noted in [12]. The CEP advocates primarily for the use of market-based re-dispatching, nevertheless it provides for specific exceptions when market-based measures are not available. These principles set a goal for the evolution of re-dispatch procedures among European TSOs, but it is also the case that current practices may deviate from pure market-based re-dispatch.

b) Balancing: The trend in the European legislation is also to impose the merit order principle in order to organize balancing. This is, for instance, explicitly stated in Article 20 and Article 21 of the regulation establishing a guideline on electricity balancing [13], articles to which the integrated European balancing platforms PICASSO and MARI, which are currently being developed, are responding.

In practice, a pure cost-minimizing real-time model may deviate, to a certain extent, from the exact operations of European TSOs. In this paper, we present and discuss a number of variations of TSO objectives in real-time operations. We insert transmission switching as one of the corrective measures that are at the disposal of the TSO in real time, as a means of mitigating congestion. These variations in the real-time model are addressed in particular in section VI and include (i) sensitivities with respect to TSO coordination, (ii) non cost-based real-time models, and (iii) a heuristic method for identifying transmission switching actions.

Once a suitable real-time model has been identified, it remains to address how the model can be solved, when transmission switching is accounted for. Previous studies on transmission switching have documented the computational challenges related to an MILP formulation of optimal transmission switching. Concretely, Hedman et al. [14] point out that, due to big-M constraints, the LP relaxation of the problem is very weak. This implies that solvers struggle in providing tight lower bounds, thereby delaying the convergence of branch and bound algorithms significantly. Different approaches have been employed in the literature in order to cope with this computational complexity. Fisher et al. [15] restrict the number of lines that can be switched off, and notice that most of the potential benefits of transmission switching can already be achieved with a limited switching budget, while the solving time is considerably reduced. Other authors have developed heuristic methods in order to obtain a high quality solution within a short amount of run time. In the work of Barrows et al. [16], Fuller et al. [17], and Wu and Cheung [18] the common idea is to resort to pre-processing in order to identify, a priori, the potential benefit of disconnecting each line in the network. This information is then used in order to solve transmission switching models where the switching actions are restricted to the most promising lines. More recently, polyhedral studies of the OTS problem have been developed. Here, a notable contribution is proposed by Kocuk et al. [19], where the authors derive a cycle-based formulation of the OTS problem. The authors use this formulation in order to derive valid inequalities that are shown to strengthen the big-M formulation,

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[1] Platform for the International Coordination of Automated Frequency Restoration and Stable System Operation.

[2] Manual Activated Reserves Initiative.

thereby decreasing the computational time for solving the problem within a certain optimality gap.

C. Paper organization

The remainder of this paper is organized as follows. Section II describes the setup of the simulations that we perform on a realistic instance of the CWE system. In section III we present a benchmark model of day-ahead zonal market clearing based on flow-based market coupling (FBMC) and discuss the impacts of transmission switching on the total cost. Then, in section IV, we discuss the sensitivity of these results against assumptions related to the N-1 robust model that is chosen (i.e. whether the dispatch is selected in a preventive or curative way with respect to a contingency). In section V we benchmark the FBMC results against a nodal market based on Locational Marginal Pricing (LMP). Section VI discusses three additional sensitivity analyses of our benchmark model with respect to: (i) the level of TSO coordination in real time, (ii) the deviations from a cost-based minimization and (iii) the number of lines that are allowed to be switched off simultaneously. Finally, section VII concludes the paper by summarizing the results of our case study and discussing the directions of future research.

II. Simulation setup

Our paper focuses on quantifying the impacts of different short-term market design options on the total day-ahead and real-time costs on a realistic instance of the Central Western European network. All simulations are performed on 32 different representative snapshots of system operation. Each snapshot corresponds to different demand forecasts, renewable forecasts and maintenance schedules (deratings) for thermal generators.

Our analysis focuses on the impact of transmission switching on mitigating costs. As we discuss in the introduction, the transmission switching problem is computationally expensive, and one means of reducing its computational burden is by imposing a *switching budget*, i.e. a limit on the number of lines that can be switched. We use a switching budget of 6 lines in our analysis.

We use the same version of the CWE system as the one used in Aravena [10]. We present the topology of the system in Fig. 1. The model consists of 6 countries: Belgium, the Netherlands, France, Austria, Luxembourg and Germany. These countries are grouped into 5 zones, with Luxembourg and Germany forming one single zone.

We separate the producing units into two sets, according to their flexibility and start-up capabilities. The on-off status of non-flexible units, which we refer to as *slow* units, is decided in the day ahead, and must be respected during real-time operations. In contrast, the production of flexible units, which we refer to as *fast* units, is independent of the day-ahead schedule. This model of unit commitment with separation between slow and fast unit follows the idea initially proposed by Ruiz *et. al.* [20] and used in subsequent unit commitment models applied both to US markets [21] and European markets [9].

The system consists of: (i) 346 slow generators with a total capacity of 154 GW; (ii) 301 fast thermal generators with a total capacity of 89 GW; (iii) 1312 renewable generators with a total capacity of 149 GW; (iv) 632 buses; and (v) 945 branches. The average demand of the system amounts to 134 GW.

The formulations of the zonal market based on flow-based market coupling that we use are generalized versions of those presented in the first part of this two-part series, and are inspired by the work of Aravena [10]. The day-ahead market clearing model considers commitment (on-off) decisions for slow generators[3], reserves and the N-1 security criterion[4].

All models and algorithms used in this study are implemented in Julia 1.0.1 [23] using JuMP 0.18.4 [24]. The models are solved with Gurobi 8.0. We parallelize the simulation over the different snapshots and we use the Lemaitre3 cluster, hosted at the Université catholique de Louvain, for the computations. The total cpu time for solving the day-ahead market clearing model with switching amounts to 10 hours and 36 minutes. We have also implemented the nested column-and-constraint approach of [25] for solving the max-min problem with MIP recourse, and record a 246% time increase compared to our proposed approach.

III. Benefits of switching in the benchmark flow-based market coupling model

In this section, we propose a benchmark model for FBMC with transmission switching and N-1 robustness and discuss the impacts of transmission switching on the total cost. As we explain in the first part of this two-part paper, the way in which the N-1 security criterion is modeled in our day-ahead zonal market clearing model depends on whether costly Remedial Actions (RA) are preventive or curative.

Definition 1. A **preventive** remedial action is an action (e.g. re-dispatching, topology measure, ...) taken by the TSO to respond to a potential contingency before the realization of that contingency.

Definition 2. A **curative** remedial action is an action taken by the TSO to react to the occurence of a contingency.

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[3] We allow slow generators to submit block bids (i.e. bids that are either entirely accepted or rejected) in the day-ahead auction.

[4] We assume that the commitment is determined along with the topology with the objective of maximizing welfare. Prices can be computed after the binary decisions have been fixed [22]. A full analysis of the implications of our zonal day-ahead model on pricing is however outside the scope of the paper, and is the subject of follow-up research.

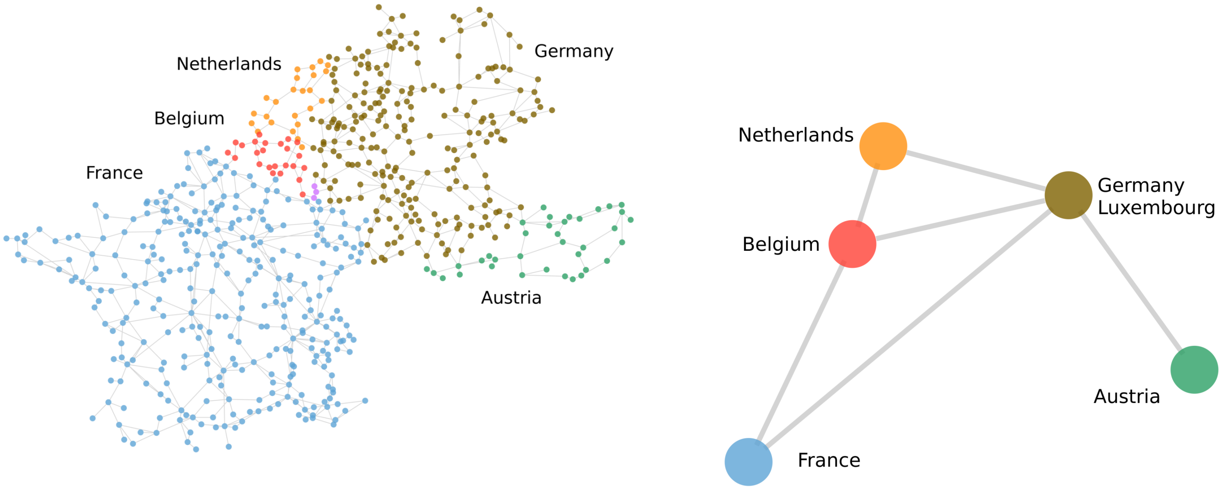

Figure 1: The CWE network model (left) and its zonal aggregation (right).

In theory, all remedial actions can be either preventive or curative [26]. In practice, however, TSOs consider that costly remedial actions (i.e. re-dispatching) should be fully preventive. As we discuss in part I, simulating FBMC with switching and a purely preventive dispatch is computationally intractable for our instance. What we propose instead is to simulate the results for a hybrid preventive-curative model that is computationally manageable. The idea of the hybrid version of the model is that the dispatch should be robust in a preventive way to a subset of contingencies, U_{prev}, and robust in a curative way to all other contingencies, $U_{\text{cur}} = U \setminus U_{\text{prev}}$. We denote the number of contingencies considered in a preventive way by n. The computational complexity of solving the hybrid day-ahead model increases with n. This number should thus be selected as the highest number that keeps the model tractable for our instance. For FBMC with switching, we identify experimentally that n should be chosen equal to 5. Our benchmark FBMC model corresponds, therefore, to a hybrid preventive-curative model with $n = 5$. The reader is referred to part I for a detailed formulation of the hybrid model as well as for a description of the algorithm used to solve it.

Let us now analyse the impacts of transmission switching on this benchmark. Fig. 2 presents the box plot of the hourly total cost of the flow-based market coupling benchmark under different assumptions about the timing of transmission switching.

Definition 3. The term **reactive switching** is used when switching is employed only in real-time operations (where it affects balancing and congestion management).

Definition 4. The term **proactive switching** is used when switching is employed both in day-ahead market clearing (where it affects the commitment of slow units) as well as real-time operations.

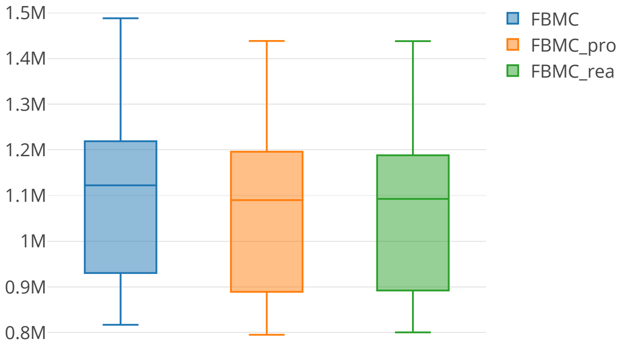

Figure 2: Hourly total cost of the different cases studied on 32 snapshots of CWE. "FBMC" refers to the case of a cost-minimizing real-time model without switching. The suffix "_rea" is for reactive (day-ahead) switching, "_pro" is for proactive (day-ahead and real-time) switching.

We do not observe any significant difference between proactive and reactive switching. On the other hand, the introduction of switching improves substantially the efficiency of operations, as compared to FBMC without switching. The annual savings of using transmission switching are evaluated at 294 M€/year, which corresponds to a 3.0% reduction in total (day-ahead and real-time) costs.

IV. Sensitivity against the security criterion model

In this section, we discuss the sensitivity of the results with respect to our assumptions about N-1 robustness. As we discuss above and in part I of the paper, different

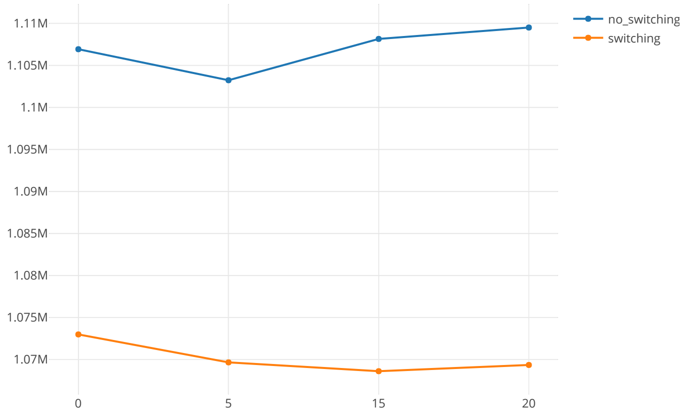

Figure 3: Evolution of the average hourly total cost on the 32 snapshots, as a function of the size of set U_{prev} in the N case. “no_switching” refers to the case of a cost-minimizing real-time model without switching, while “switching” corresponds to reactive switching.

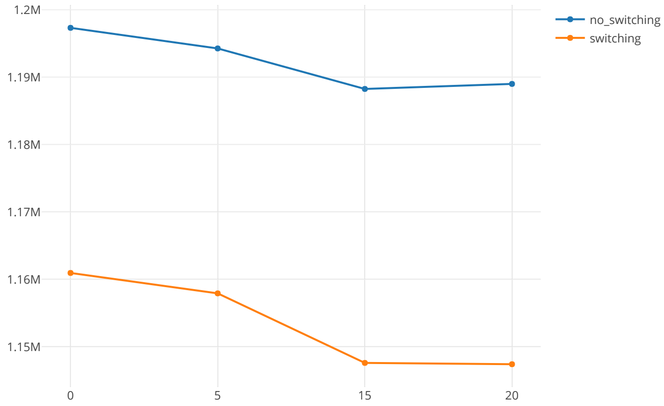

Figure 4: Evolution of the average hourly total cost on the 32 snapshots, as a function of the size of the set U_{prev} in the N-1 case. “no_switching” refers to the case of a cost-minimizing real-time model without switching, while “switching” corresponds to reactive switching..

assumptions on whether the TSO resorts to preventive or curative remedial actions lead to different FBMC models. Based on this distinction, in section III, we propose a benchmark that corresponds to a hybrid preventive-curative model. The size of the preventive set U_{prev}, which we denote by n, needs to be determined so as to maintain a tractable day-ahead market clearing model when switching is considered. As we show in section 3, the difference between proactive and reactive switching is negligible. We therefore focus on the case of reactive switching, which is computationally less demanding, and analyse the evolution of the total cost with respect to n.

Fig. 3 presents the evolution of the average hourly total cost on the 32 snapshots, as a function of n. We observe that the different choices of n exhibit similar performance, both for the situation with as well as without switching. The largest difference in total cost is observed for the case without switching, and amounts to less than 0.5%.

The results presented in Fig. 3 correspond to the results for the base case, i.e. the case where no contingency occurs in real time. As the models with different n differ in how they cope with N-1 robustness, we are also interested in analyzing an N-1 case in real time, i.e. a situation where a line is lost between the day ahead and real time. We focus our analysis on a contingency that is hard for each model. For this purpose, we analyse the contingencies that are generated during the column-and-constraint generation algorithm that is described in section 4 of Part I. We identify a specific contingency that appears to be consistently severe. This line corresponds to a cross-border line between Avelgem in Belgium and Avelin in France.

In Fig. 4 we present the equivalent of Fig. 3 for the N-1 case. The efficiency gap between purely curative N-1 robustness and the hybrid case with $n = 20$ now increases to 0.8% in the case without switching, and to 1.2% in the case with switching. We note that cases $n = 15$ and $n = 20$ are almost identical. This suggests that considering 20 lines in the definition of set U_{prev} may be sufficient, since the results appear to reach a stable behavior with 15 preventive contingencies. We further note that the benefits of reactive switching in FBMC are more important than in the N case, and amount to 3.5%.

V. Benchmarking of the results against a nodal market

In this section, we benchmark our results against a nodal LMP-based market model. The model maintains the same two-stage structure as the zonal model that we have analyzed so far: unit commitment for slow units is determined in the day ahead, and re-dispatch and balancing are decided in real time. The difference with the zonal model is that the day-ahead unit commitment is now determined under a full nodal network model that includes all transmission constraints. Similarly to [27], we define N-1 security for LMP markets as the ability of a system to withstand any single-element transmission contingency, while maintaining its current nodal injections and without violating any security constraints. Unlike in zonal markets, proactive transmission switching is currently not applied in practice in nodal electricity markets (e.g. the US market) to the best of our knowledge. Therefore, we simulate only reactive switch-

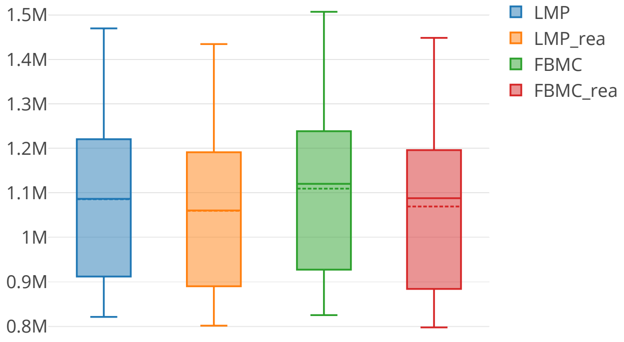

Figure 5: Hourly total cost of the different cases studied on 32 snapshots of CWE in the N case. “FBMC” refers to the case of a cost-minimizing real-time model without switching. The suffix “_rea” is for reactive switching.

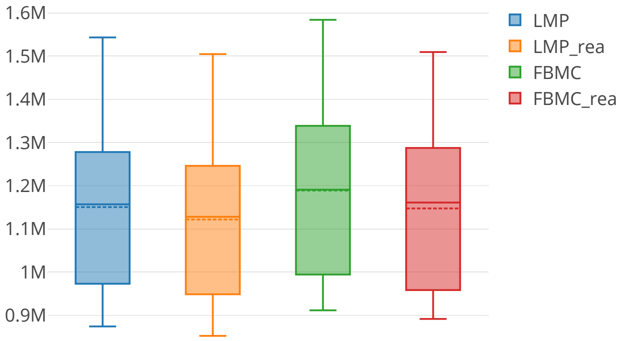

Figure 6: Hourly total cost of the different cases studied on 32 snapshots of CWE in the N-1 case. “FBMC” refers to the case of a cost-minimizing real-time model without switching. The suffix “_rea” is for reactive switching.

ing for the LMP benchmark. We use the same cutting-plane algorithm as the one developed in [27] for clearing the N-1 secure nodal unit commitment model.

Hereafter, we compare the results of LMP and the best FBMC model (i.e. reactive switching with hybrid dispatch and $n = 20$) in the N state (i.e. no contingency). Fig. 5 presents the box plot of the 32 snapshots for both LMP and FBMC, with and without reactive switching. As there is a significant difference between the mean and the median for the FBMC model, we also display the mean in a dashed line.

The first observation based on these results is that, when no contingency occurs, transmission switching contributes partially towards recovering the gap between nodal and zonal pricing. This gap is evaluated in our analysis at 2.1% (difference of “LMP” and “FBMC”) when there is no reactive switching, and decreases to 0.9% (difference of “LMP_rea” and “FBMC_rea”) with reactive switching. This translates to annual savings of 208M€ and 85M€ respectively. We thus observe that the benefits of switching are greater in the zonal setting than in the nodal setting, which is aligned with intuition.

The situation differs in the case where a contingency occurs in the system. Fig. 6 is the equivalent of Fig. 5 when a transmission line contingency has occurred. As in the case of section 4, we consider a failure of the cross-border line between Avelgem (Belgium) and Avelin (France). Under this contingency, the gap between LMP and FBMC increases to 3.2% without switching, and to 2.2% with reactive switching. This suggests that the dispatch obtained with the nodal model is more robust to contingencies than that obtained by FBMC.

VI. Additional sensitivities

A. *Sensitivity on TSO coordination*

In order to represent the possibility that the real-time operations of TSOs may not be perfectly coordinated, we fix day-ahead net positions of each zone to the result of the day-ahead market, and assume that each TSO is responsible for identifying re-dispatch and balancing actions that relieve congestion, *while maintaining the day-ahead net position* of its zone.

Note that this assumption is in line with the European viewpoint that considers the day-ahead market as the spot market, and relegates re-dispatch and balancing to a set of services that are deployed for supporting the spot market positions. In recent years, this view has been relaxed with the emergence of a liquid intra-day market in Central Wester Europe and with the move towards integrated pan-European platforms for balancing. As we demonstrate in the following paragraph, the view of treating the day-ahead market as the spot market for trading is detrimental towards efficiency, and there is therefore great value in coordinating inter-zonal dispatch closer to real time.

In Fig. 7 we present the results of re-dispatch and balancing both for the case where the net positions are free to deviate, and also for the case where they are fixed to their day-ahead values. Two interesting observations can be made, based on Fig. 7. The first one is that TSO coordination has considerable value. In the case without any switching action, the annual benefits of coordination are evaluated at 596M€. The second interesting observation is that the benefits of switching are significantly more important when the net positions are fixed. Whereas the cost decrease due to reactive switching with a budget of 6 lines amounts to 3.0%, this value increases to 6.6% if we assume that the

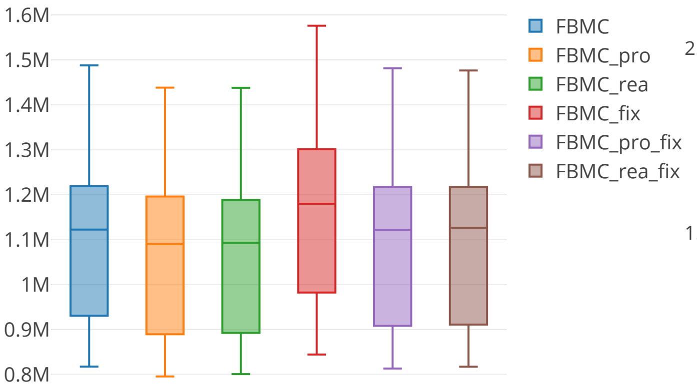

Figure 7: Hourly total cost of the different cases that are studied on 32 snapshots of CWE. The suffix "_fix" refers to the case where the net positions are fixed to their day-ahead values.

net positions of the day ahead must be maintained in real time.

B. *Deviations from cost-minimization*

In contrast to the transmission-constrained economic dispatch which takes place in real-time US operations, assuming that TSOs use a perfect cost-minimization in real time may not be the case in practice in European system operations, both due to the fact that (i) certain European TSOs do not use optimization algorithms in real time, but also because (ii) real time is not necessarily perceived as an "appropriate moment" for economic trade to take place. We thus simulate the two following variants. (i) In order to represent the view which supports that real time should be used for balancing the system, and not enhancing economic trade, we simulate a volume-based model, where the objective is to minimize the deviation with respect to the day-ahead schedule. (ii) In order to represent the fact that certain TSOs do not use optimization algorithms, but rather heuristics, for determining real-time set-points, we simulate a PTDF-based heuristic for re-dispatching and balancing the system. Both models are presented in detail in appendix section B.

Fig. 8 presents the performance of a cost-minimizing real-time model with the performance of alternative methods. These results demonstrate that the assumptions about how re-dispatch and balancing are performed have a very significant impact on the analysis. Clearly, the perfectly coordinated cost-minimizing real-time model is the golden standard and outperforms the alternative methods by a large margin. It is worth pointing out that the relative advantage of using transmission switching is much less significant than the effect of using a real-time method that is aimed at operational efficiency. For instance, Fig. 8 illustrates that the minimum volume model is almost insensitive to the method of switching that is used.

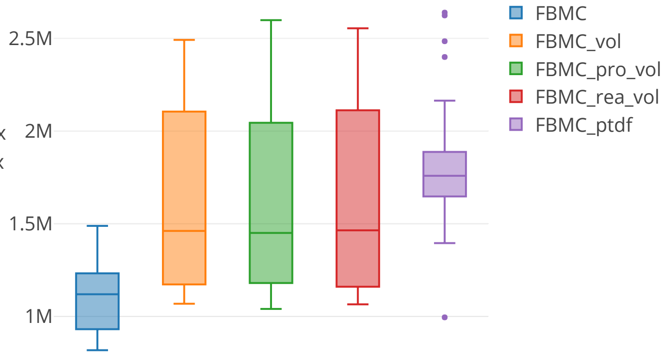

Figure 8: Hourly total cost of the different re-dispatch and balancing methods on 32 snapshots of CWE. In this figure, the "FBMC" series refers to the same series as the "FBMC" series of Fig. 2, i.e. a cost-minimizing real-time model without switching. The suffix "_vol" is for the volume-minimizing real-time model, "_ptdf" is for the PTDF-based heuristic. Note that, for the latter, there is no switching action possible, as it is based on the PTDF obtained for a reference topology.

C. *Switching more lines with a heuristic method*

An important observation that is discussed in section V and demonstrated in Fig. 6, is that when a severe contingency occurs in the system, the gap between LMP and FBMC when reactive switching is allowed is still significant (more than 2%). As the benefits of switching have been found to be more important for FBMC, we might wonder whether this finding is sensitive to the number of lines that can be switched. Recall that we use a switching budget of 6 lines for this study. We solve the real-tile models to a MIP gap of 1% in order to keep the computation tractable. We now consider the LMP-based heuristic presented by Fuller et al. [17] as an alternative real-time switching heuristic. We describe this heuristic in detail in section A of the appendix. The number of lines that can be switched off is indicated by parameter Max_iter in Algorithm 1 of appendix A. We set this parameter to 40, thereby allowing up to 40 lines to be switched. This parameter is validated *a posteriori* by checking that it is never binding, i.e. that the best result is obtained at an iteration strictly less than 40.

Fig. 9 demonstrates that it can indeed be beneficial to switch more than 6 lines. For FBMC, we evaluate this benefit at 50M€ annually, which corresponds to less than half a percent. However, the LMP-based market

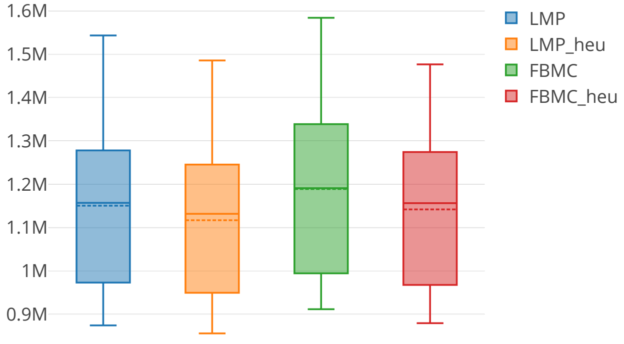

Figure 9: Hourly total cost of the different cases studied on 32 snapshots of CWE. The suffix "_heu" refers to the results when Fuller's heuristic is used, as described in Algorithm 1 in appendix.

clearing still outperforms FBMC with reactive switching in the N-1 case when both models use Fuller's switching heuristic. The efficiency gain of LMP remains at 2.2%, the same as with the budget method.

VII. Conclusion

In the first part of this paper, we have proposed a two-stage model of a zonal electricity market with transmission switching at both the day-ahead and real-time stage. We have cast the problem as a robust optimization problem (ARO) with mixed integer recourse, and we have described a novel algorithm for solving ARO problems with mixed integer recourse that respect a certain structure. We apply the algorithm to the case of day-ahead market clearing with proactive line switching.

In this second part, we propose a benchmark FBMC model, and we analyze the impacts of both proactive and reactive transmission switching on the operating costs of a realistic case study of the Central Western European system. We then perform a detailed sensitivity analysis in order to identify the sensitivity of our results on various assumptions related to short-term electricity operations. In particular, we consider (i) the influence of preventive versus curative security practices, (ii) the impact of contingencies, (iii) the level of TSO coordination and (iv) deviations from real-time cost minimization.

We summarize below the main observations that we can draw from our case study:

- The performance of proactive and reactive switching are similar.
- The number of contingencies that are considered in a preventive way in the day-ahead market clearing problem influences significantly the total cost when a contingency occurs in real time. This improvement is evaluated at 1.2% for reactive switching.
- Transmission switching benefits is more beneficial for FBMC than for LMP. Considering transmission switching thus contributes towards recovering partially the efficiency gap between zonal and nodal market clearing. This gap is estimated at 1% in the N case, but increases to 2.2% in the N-1 case under the occurrence of a severe contingency.
- The impact of TSO coordination is significant, and is more important in the absence of transmission switching.
- Performing re-dispatch and balancing without aiming at operational efficiency may eclipse the potential efficiency gains of transmission switching.

We have not discussed the potential pricing and policy issues that can arise as a consequence of the additional non-convexities that are introduced to the market clearing procedure by transmission switching. These, however, are important questions that were already partially discussed in [22]. Further research is needed in order to develop a viable framework for quantifying the impact of transmission switching on market clearing prices.

Appendix

For an explanation of the notation used in the following models, we refer the reader to part I.

A. Heuristic switching algorithm

We use the LMP-based heuristic presented by Fuller *et al.* [17] as an alternative real-time switching heuristic. The algorithm is summarized as follows.

Algorithm 1: LMP-based switching heuristic

```
1) Set $k = 0$ and $\mathcal{O}_k = \emptyset$, where $\mathcal{O}_k$ is the set of lines that are disconnected, at iteration $k$.
2) Obtain ranking parameter $\alpha_l$ for all lines $l \in L$ as follows:
    • Fix the topology as $z_l = 0$ if $l \in \mathcal{O}_k$ and $z_l = 1$ otherwise and solve the corresponding real-time model, which is an LP.
    • Let $\pi_n$ be the LMP of node $n$. Let $\alpha_l = \pi_{m(l)} - \pi_{n(l)}$
3) Solve the following switching problem, with a subset
```

of the lines fixed:

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

4) Let $k \leftarrow k+1$. If $k \geq Max\_iter$, stop. Else, go back to step 2.

B. Non cost-based re-dispatch and balancing

1) Volume-based heuristic: The volume-minimizing model can be straightforwardly described with the same constraints as the cost-minimizing model that is presented in section 3-C of part I. Instead, the objective function now corresponds to minimizing the total deviation from the day-ahead dispatch. The motivation for this model is the fact that European market operations prioritize the balancing of portfolios as real time approaches. The model can be described as follows:

$$
\begin{aligned}
\min_{\substack{v\in[0,1]\\ f,\theta,\\ t\in 0,1}} \; & \sum_{g\in G} Q_g \left| v_g - v_g^{\mathrm{DA}} \right| \\
\text{s.t.} \; & \sum_{g\in G(n)} Q_g v_g - \sum_{l\in L(n,\cdot)} f_l + \sum_{l\in L(\cdot,n)} f_l = Q_n, \\
& \hfill \forall n \in N \\
& -F_l t_l \leq f_l \leq F_l t_l, \quad \forall l \in L \\
& f_l \leq B_l(\theta_{m(l)} - \theta_{n(l)}) + M(1-t_l), \quad \forall l \in L \\
& f_l \geq B_l(\theta_{m(l)} - \theta_{n(l)}) - M(1-t_l), \quad \forall l \in L
\end{aligned}
$$

Here, v_g^{DA} is the acceptance/rejection of generator g in the day-ahead process. It is fixed as a parameter for the real-time model.

2) PTDF-based heuristic: The idea of the PTDF-based heuristic that we propose for approximating the fact that certain TSOs do not employ optimization in real time is to use the PTDF matrix of the system in order to identify, for each overloaded line, the generators that contribute the most to the flow on this line. For these generators, we can compute the amount of reduction in production that is necessary in order to alleviate congestion on the line. By doing so, it is possible that other lines will be affected. We thus iterate over this process until no more lines are congested, as shown in Algorithm 2.

Algorithm 2: CRH (Congestion Removal Heuristic)

```
Input: initial dispatch $v$
Output: new dispatch that respects network constraints
let $L_{\text{cong}}$ be the set of congested lines, sorted by congestion magnitude
while $L_{cong} \neq \emptyset$ do
    for every $l \in L_{cong}$ do
        let $N_{\text{sorted}}$ 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 $L_{\text{cong}}$
```

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