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# Manual Frequency Restoration Reserve Activation Clearing Model

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**Abstract:** The integration of the European markets has started with the successful coupling of spot markets (day-ahead and intra-day) and is expected to continue with the coupling of balancing markets. In this paper, the optimization model for the activation of manual frequency restoration reserve (mFRR) is presented. The model incorporates all order types agreed among the European transmission system operators (TSOs) to be included in the Manually Activated Reserves Initiative (MARI) project. Additionally, the model incorporates the buying curve (demand) of mFRR with the possible tolerance band defined by the TSOs, order clearing constraints and the cross-zonal capacity (CZC) constraints, forming a mixed integer linear programming model. The methodology employs two distinct steps: In the first step, an order conversion process is employed for the markets applying the central-scheduling scheme, and in the second step, the mFRR activation process is executed by solving the presented model. The whole process is tested using a case, including twenty-five European control areas. The attained clearing results indicate that price convergence is achieved among the involved control areas, along with a reduction in the overall balancing costs mainly due to the imbalance netting that is implicitly performed during the joint mFRR balancing energy (BE) clearing process and due to the cross-border exchange of mFRR BE.

**Keywords:** balancing market coupling; balancing energy orders; cross-border balancing energy exchange; manual frequency restoration reserve; order conversion process; common merit order list; activation optimization function



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## 1. Introduction

Maintaining the real-time balance between the power generation and consumption is a rather challenging task entrusted to transmission system operators (TSOs). Due to the non-storability of electricity, imbalances that occur (due to technical reasons, e.g., power plant outages/transmission lines failures, load and/or renewable forecasting errors, etc.) between generation and consumption cause the grid frequency to deviate from its respective nominal target value of 50 Hz. To restore such balance and guarantee secure operation of the electricity grid, TSOs are responsible for continuously monitoring the system conditions and taking the appropriate remedial actions when needed. Within this context, TSOs rely on the procurement and activation of four main types of balancing services: (a) frequency containment reserve (FCR), which is activated during the first seconds (up to 30 s) after the occurrence of an event and is used to stabilize the grid frequency to a new acceptable level close to the nominal value; (b) automatic frequency restoration reserve (aFRR), which is used to fully restore the required grid frequency and is activated up to 5–7.5 min after an event; (c) manual frequency restoration reserve (mFRR), which is used to release the aFRR and is activated up to 12.5–15 min after an event; and (d) replacement reserve (RR), which is used to release or support the required level of frequency restoration reserve (FRR) so as to be prepared for additional imbalances and is activated from 30 min up to 60 min after an event. Figure 1 [1] below schematically depicts the activation sequence of the four available types of balancing services in accordance with

"Commission Regulation (EU) 2017/1485 of 2 August 2017, establishing a guideline on electricity transmission system operation (SO)" [2].

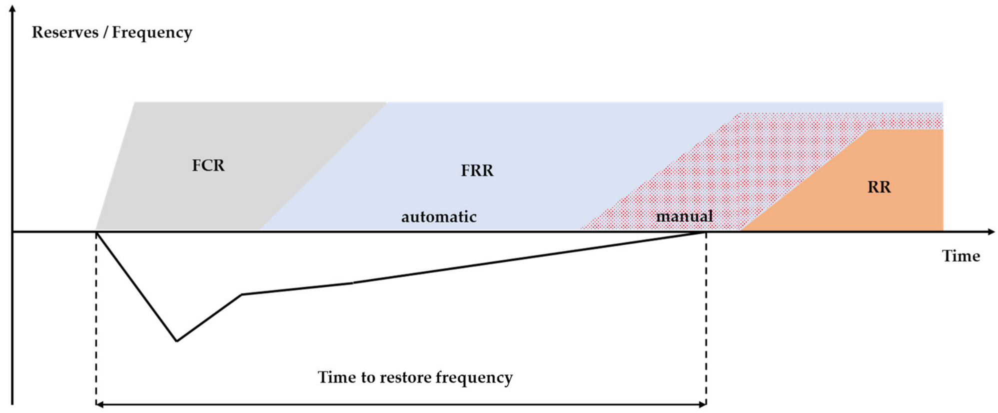


**Figure 1.** Load frequency control processes.

These services may be delivered by balancing service providers (BSPs) that have been successfully completed the pre-qualification processes and meet the necessary technical requirements. Until now, in most European countries, these balancing services are provided only by local BSPs in each load frequency control area (LFC area). However, considering the newly established provisions/guidelines of the European Commission, a more broad, or even pan-European coupled regime, shall be adopted among the control areas of the member states. At this point, it is important to note that according to the guidelines, an mFRR balancing energy order (BEO) is submitted at the lowest possible level between the bidding zone and LFC area. If an LFC area consists of several bidding zones (e.g., Italy), then the location of the bid shall be provided per bidding zone. If a bidding zone consists of several LFC areas (e.g., Germany), then the location of the bid shall be provided per LFC area. In order to maintain a single terminology for the submission of the BEOs and the TSO needs, the term "control area" shall be used throughout this paper, even for the location where BEOs are submitted (namely the "bidding zone").

To put it more precisely, the European Commission has set an ambitious goal of integrating all the European electricity markets at all of the timeframes. To do so, it has drafted and issued the respective regulations establishing the required guidelines. Concerning the balancing markets, the technical and operational specifications for their integration are provisioned in the "Commission Regulation (EU) 2017/2195 of 23 November 2017 establishing a guideline on electricity balancing (EBGL)" [3].

Within the framework of the balancing market integration, various cooperation pilot projects have been initiated between European TSOs. To begin with, the FCR project [4] is a project including ten TSOs from seven countries. The settlement approach of this project is the TSO–TSO model, and the balancing services are being provided through a common merit order list (CMOL) where all of the balancing energy orders (BEOs) of the participating BSPs are gathered for clearing.

Another project already applicable in Europe is the International Grid Control Cooperation (IGCC) project [5]. This project aims to improve the efficiency of balancing between the control areas of Austria, Belgium, Croatia, Czech Republic, Denmark, France, Germany, the Netherlands, Switzerland and Slovenia by taking advantage of the imbalance netting of the aFRR needs. Essentially, the IGCC compensates for any imbalances experienced in opposite directions between these TSOs.

A third project is the Platform for the International Coordination of Automated Frequency Restoration and Stable System Operation (PICASSO) project [6], which concerns the exchange of aFRR between European control areas. Additionally, in this project, a TSO–TSO approach is adopted and the respective the services are being procured through a CMOL.

Additionally, the project called the Manually Activated Reserves Initiative (MARI) [7] constitutes the basis project for the exchange of balancing energy (BE) from an mFRR. As for now, 30 TSOs are actively participating and another four are observers to this project. Briefly, the high-level conceptual design of the MARI constitutes the following [8]: (1) the BSPs submit their mFRR BEOs to the respective TSO; (2) the TSOs send the BEOs, the calculated CZCs and their mFRR balancing needs to the MARI platform; and finally, (3) an activation optimization function clears the auction providing the mFRR BE clearing prices, the BEOs are activated in each control area and the CZCs are used in each interconnection. In addition to this reference project, other regional implementation projects have been initiated by specific TSOs, which facilitate in such way the European market integration and an improved balancing market efficiency by sharing their valuable experience gained from these regional synergies. More specifically, in January 2019, the Nordic TSOs began the project named "Nordic Balancing Model" [9] in order to implement a voluntary Nordic mFRR balancing energy activation market. In addition, the German and Austrian TSOs have been developing a voluntary cooperation to optimize the activations of mFRR BEOs between these two countries [1]. This project, called "GAMMA", went live on 4 December 2019 [10].

Lastly, the Trans European Replacement Reserves Exchange (TERRE) project [11] constitutes the respective reference project for the cross-border exchange of BE from a RR. The core scope of this project is to set up a common clearing platform which collects all the RR BEOs from the participating TSOs and provides the activations of the RR in order to cover all of the TSOs' RR BE needs. Again, in this project, the TSO–TSO model [12] is applied.

Currently, only the TERRE platform (also called the "LIBRA" platform) has been launched since 6 January 2020 and six balancing markets (Czech Republic (CEPS), France (RTE), Italy (Terna), Portugal (REN), Spain (RED) and Switzerland (Swissgrid)) have successfully been coupled, enabling in such a way the cross-border BE exchange from the RR. The launch of the TERRE platform was the first step towards the completion of the European Commission's vision. The other platforms are in the development phase, and it is worth mentioning that it is expected that the same solution (the LIBRA platform) will be used for both the MARI and the PICASSO with the appropriate modifications [13].

This paper presents the mathematical programming model that simulates the objective function and the respective constraints of the mFRR BE activation process (i.e., the MARI project). As far as the literature is concerned, various studies have been conducted to analyze and highlight the potential gains of a cross-border BE exchange between the European countries. More specifically, [14] performs a model-based analysis for the exchange of reserves between Norway and Germany. In the same vein, [15,16] present optimization models for the exchange of BE between the Nordic countries while [17] examines the same concept for the Northern European continent, including the Nordic countries, Germany and the Netherlands. In [18], a mathematical model for coupled balancing markets is proposed and it is implemented for a case study which includes Austria, Italy and Slovenia. The publication from [19] analyzes, on a qualitative basis, the algorithm design principles of the MARI, presenting a mathematical formulation of the optimization problem. Additionally, in [20] a model for the activation optimization function (AOF) of an mFRR platform is defined. Table 1 summarizes the specific features of the research works presented above and provides a comparison with the respective features presented in this paper. The first feature concerns the adoption of a central-scheduling or self-scheduling market setup; this relates to the way in which the scheduling process of the entities (e.g., generating units, demand response entities, dispatchable RES, etc.) is performed in day D-1 for dispatch day D and also during intra-day. In the central-scheduling scheme, the TSO executes centrally the scheduling process, called the integrated scheduling process (ISP), to cover the forecasted system imbalance for each scheduling period of the dispatch day D, to cover the system reserve requirements and to relieve any forecasted congestions in the transmission grid. In the self-scheduling scheme, each participant who owns/operates dispatchable entities/portfolios (called BSP) self-schedules its dispatchable entities/portfolios to cover the energy quantities sold/bought in the forward and spot markets. The self-schedules are gathered by the TSO through a nomination platform, which then may activate upward or downward the dispatchable entities/portfolios (re-dispatching) for system balancing purposes or for system security (non-balancing} purposes. The difference between the two schemes is that in markets organized with the central-scheduling scheme, the BSPs submit simple quantity–price BEOs in the ISP, which are also available in the real-time dispatch process, but they must be appropriately converted in order to be considered for clearing in the real-time dispatch process. In the self-scheduling scheme, there is no ISP nor any BEOs submitted for the ISP; there are simply BEOs submitted for the real-time dispatch process, which are fully compliant with the "standard products".

**Table 1.** Main features of the research works presented in the literature.

| Ref. | Central-/Self-Scheduling Scheme | Perform Orders' Conversion Process | Type of Orders Modeled | Handling of Paradoxically Accepted Orders | Modeling Tolerance Band | Modeling of Interconnection Controllability |
|---|---|---|---|---|---|---|
| [14] | not specified | no | not specified | no | no | no |
| [15] | not specified | no | not specified | no | no | no |
| [16] | not specified | no | not specified | no | no | no |
| [17] | not specified | no | not specified | no | no | no |
| [18] | not specified | no | only fully divisible | no | no | no |
| [19] | not specified | no | all | no | no | no |
| [20] | not specified | no | only fully divisible | no | no | no |
| This paper | both | yes | all | yes | yes | yes |

Based on the features presented in Table 1, the main novelty of the herein presented research work constitutes the analytical mathematical modeling of the mFRR BE clearing module incorporating all order types and modeling features introduced in the MARI. Specifically, the main contributions of this work comprise:

(a) The incorporation of all BEO types as defined in the guidelines of the MARI project and the analytical presentation of the mathematical equations of their clearing conditions;
(b) The consideration of both self-scheduling and central-scheduling markets in the same modeling framework; for the latter, the BEOs submitted by BSPs are being converted to "standard products" by the respective TSOs before the mFRR BE clearing process, as required by EBGL;
(c) The modeling of the conversion process for the preparation of the BEOs, before entering the mFRR BE clearing process;
(d) The modeling of interconnection controllability;
(e) The modeling of the TSO-defined tolerance band in the clearing model constraints;
(f) The incorporation of elastic and inelastic orders defined by the TSOs to satisfy their mFRR balancing energy needs.

## 2. Balancing Processes and Timings

In this Section, the balancing processes and the respective timings that are expected to be enforced in accordance with the guidelines [21,22] are presented in detail. For a specific real-time unit (RTU), i.e., a quarter-hour (see blue area in Figure 2 below), BSPs may start submitting their BEOs to their connecting TSOs, for providing aFRR and mFRR, from dispatch day D-1 at 12:00 until 25 min before the beginning of the concerned RTU in dispatch day D. For the RR BEOs submission process, the gate opening time and the gate closure time are 70 min and 55 min before the concerned RTU, respectively.

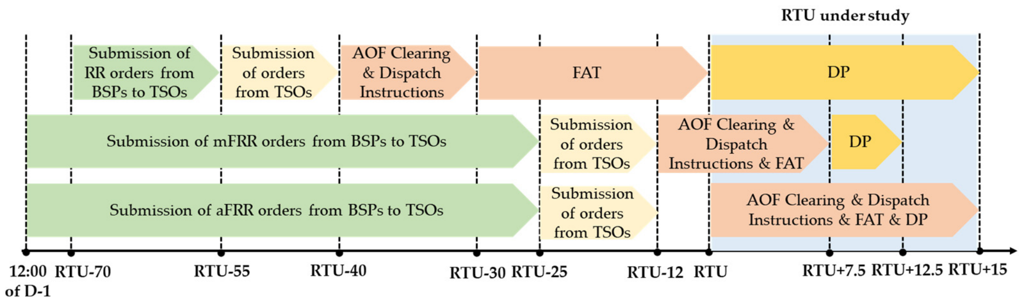


**Figure 2.** Illustration of the sequence of the balancing processes and the respective timings.

After each mFRR BEO submission gate closure time, the TSOs perform(locally)pre-processes with the BEOs they receive, make them anonymous and forward them to the respective European platform in order to be included in the mFRR BE clearing process. It should be noted that the TSO gate closure time for the submission of the processed and anonymized aFRR and mFRR BEOs to the respective European platforms shall be 12 min before the beginning of the concerned RTU, meaning that the duration of the orders' pre-processing must take at maximum 13 min (i.e., from RTU-25 until RTU-12). During such processing time, the TSOs of control areas applying a central-scheduling scheme shall have to complete the orders' conversion process as required by Article 27 of the EBGL. In the RR process, the gate closure time is different; the TSOs are required to process and forward the submitted RR BEOs to the European platform 40 min before the concerned RTU. Thus, the duration of the processing must take at maximum 15 min (i.e., from RTU-55 until RTU-40).

Along with the BEOs, the TSOs are also responsible for sending to the mFFR BE clearing platform their mFRR needs and the respective available CZCs as resulted after the clearing of the spot markets. In accordance with the implementation framework the participating TSOs may submit inelastic and/or elastic orders. TSOs, among others, may submit other data, such as the tolerance band, the interconnection controllability and the loss factors of direct current (DC) interconnections. Once all this data has been submitted, they are inserted into the mFRR BE clearing platform, which solves the mFRR BE clearing problem and provides the respective clearing results.

Based on the clearing results, the TSOs receive the results and issue appropriate dispatch/activation instructions to the BSPs. At this stage, it is crucial to point out the importance of the full activation time (FAT) and the delivery period (DP) [1]. The FAT corresponds to the period between the activation instruction by the TSO and the respective full delivery of the requested quantity of the concerned BSP's BEO, whereas the DP concerns the period during which a BSP delivers the full/maximum quantity. Both characteristics differ between the three balancing processes. In the RR BE clearing process, the FAT is equal to 30 min and the DP is equal to 15 min, and in the mFRR BE clearing process, the FAT is equal to 12.5 min and the DP is equal to 5 min. Finally, in the aFRR BE clearing process the FAT and DP are jointly equal to 5 min. Figure 2 below schematically depicts the interaction between the relevant balancing processes as well as the respective timings.

## 3. mFRR Platform Order Types

In accordance with [21], there are specific types of orders that can be submitted by the BSPs in the mFRR BE clearing platform in both the upward and downward direction, which are as follows:

- Fully divisible/divisible/indivisible orders: For these types of orders, the same rules and clearing conditions apply as the respective set of fully divisible/divisible/indivisible orders that can be submitted in the LIBRA platform for the RR BE activation. The only difference is the validity period of the order, which is equal to one RTU (15 min), while in the LIBRA platform the submitted orders can be valid for four RTUs. Therefore, a one-shot 15 min clearing for mFRR BE activation is feasible and likewise presented in this paper, whereas for the RR BE activation, a forward-looking solution incorporating four 15 min intervals in necessary [23]. An analytical conceptual description of these order types can be found in [23].

- Exclusive in volume orders: Similarly, for this order type, the same rules and clearing conditions apply as the respective set of exclusive in volume orders that can be submitted in the LIBRA platform for the RR BE activation. The analytical conceptual description of this order type is again presented in [23].
- Multi-part or parent–child order: This order type concerns the combination of an indivisible parent order (see grey area in Figure 3a,b) with a divisible (see blue area in Figure 3a) or indivisible (see blue area in Figure 3b) child order submitted for a specific RTU. These two orders may bear different quantities and prices. In addition, the child order can only be activated if the parent order is activated as well, not vice versa. To put it differently, the acceptance of a subsequent order can be made dependent on the acceptance of the preceding order. This parent–child linking could be useful for power generators in order to more accurately model the technical/operating constraints of their conventional (thermal or large hydro) generating units. It is worth referring that this type of order (multi-part) has a different meaning/definition from the respective multi-part orders submitted in the LIBRA platform for the RR BE activation, as referred in [23].

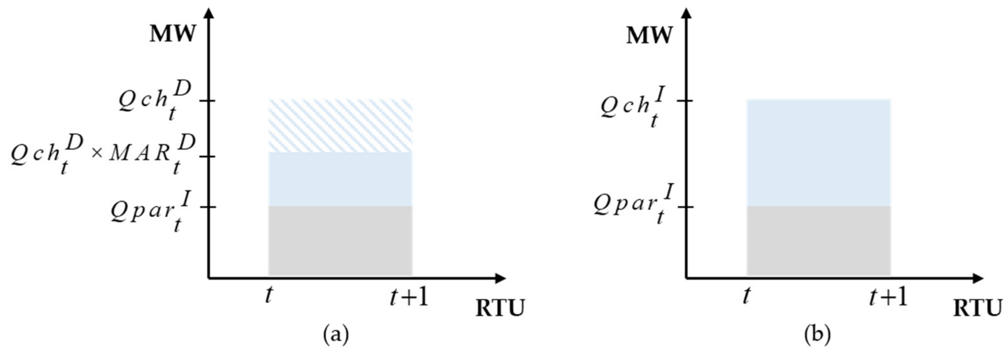


**Figure 3.** (**a**) Indivisible parent order and divisible child order; (**b**) Indivisible parent order and indivisible child order.

## 4. Conversion Process of BEOs for Control Areas Applying Central-Scheduling Scheme

In Article 27 of the EBGL, it is provisioned that the TSOs applying a central-scheduling scheme must convert the BEOs submitted by BSPs for the ISP in the afternoon of dispatch day D-1 into "standard products" before forwarding them to the respective platform for clearing. In accordance with Article 2 of the EBGL, "standard product" means a harmonized balancing product defined by all of the TSOs for the exchange of BE from a specific reserve type (in our case from mFRR). This conversion process is deemed necessary for the successful integration of these central-scheduling control areas into the pan-European balancing platforms, as well as for their reliable and secure operation and management [24].

Within this context, in this paper, a conversion process is implemented for countries applying central-scheduling scheme (e.g., Greece, Italy, Poland), based on the research work carried out by the authors in [25] for the conversion of RR BE orders. In this Section, the authors present the equations and constraints of the orders' conversion optimization problem, which is fully compatible with the provisions and requirements of the mFRR BE clearing process.

The objective of the mFRR BEOs conversion process is to maximize the mFRR BE quantity that can be offered for clearing (in the subsequent mFRR BE clearing problem) by the BSPs in both directions (upward and downward).

$$\mathrm{Max}\left\{\sum_{bse\in \mathrm{BSE}}\ \sum_{t\in \mathrm{T}}\left[\mathrm{mFRR}^{up}_{bse,t}+\mathrm{mFRR}^{dn}_{bse,t}-(\mathrm{s}_{bse,t}+\mathrm{d}_{bse,t})\cdot \mathrm{P}^{viol}_{bse,t}\right]\right\} \tag{1}$$

In accordance with the respective balancing processes, mFRR BE clearing shall be executed every 15 min for the following RTU (single period optimization) while the RR BE clearing shall be executed every hour for the four RTUs of the following hour. For this reason, the index $t$ can be omitted from all of the symbols presented in the herein presented formulation; nevertheless, it has been retained for homogeneity purposes. Taking this into consideration, the mFRR BE conversion process shall be also executed every 15 min for the following RTU and before the respective mFRR BE clearing process in order to attain the adjusted maximum quantities of the submitted BEOs.

Constraints (2)–(11) are incorporated in order to limit the upward/downward mFRR BE quantity offered by BSPs, so that the final dispatch instructions (that shall be issued after the mFRR BE clearing process, considering any possible activation of both the RR BE and the herein offered mFRR BE) respect the BSPs' technical minimum and maximum power output. More specifically, in constraint (2), the maximum downward mFRR BE that can be offered by a BSP in a specific RTU lies between the market schedule and the respective lower technical limit in each operating state (i.e., synchronization, soak, normal dispatch or desynchronization), while also taking into consideration: (a) the downward FCR and aFRR reserve quantities that have already been awarded to said BSP, and (b) the already activated downward RR BE of the BSP for the given RTU.

In the same vein, in constraint (3), the maximum upward mFRR BE lies between the market schedule and the respective upper technical limit in every operating state, while also taking into account (a) the upward FCR and aFRR reserve quantities that have already been awarded to said BSP, and (b) the already activated upward RR BE of the BSP for the given RTU.

It is noted that both the upward and downward RR BE can be activated either by the preceding RR BE clearing process or manually by the TSO during the mandatory activation process.

The respective constraints (4) and (5) apply for the BSPs which are operating under automatic generation control (AGC) in the specific RTU.

$$\begin{aligned}&\mathrm{MS}_{bse,t}-\mathrm{mFRR}^{dn}_{bse,t}-\overline{\mathrm{rr}^{dn}_{bse,t}}-\overline{\mathrm{s}^{rr}_{bse,t}}-\overline{\mathrm{Q}^{FCR^{dn}}_{bse,t}}-\overline{\mathrm{Q}^{aFRR^{dn}}_{bse,t}}+\mathrm{d}_{bse,t}\\&\geq 0\cdot\overline{\mathrm{u}^{syn}_{bse,t}}+\mathrm{P}^{soak}_{bse,t}+\mathrm{P}^{des}_{bse,t}+\mathrm{P}^{\min}_{bse,t}\cdot\overline{\mathrm{u}^{disp}_{bse,t}} \qquad \forall bse\in \mathrm{BSE}, t\in \mathrm{T}\end{aligned} \tag{2}$$

$$\begin{aligned}&\mathrm{MS}_{bse,t}+\mathrm{mFRR}^{up}_{bse,t}+\overline{\mathrm{rr}^{up}_{bse,t}}+\overline{\mathrm{d}^{rr}_{bse,t}}+\overline{\mathrm{Q}^{FCR^{up}}_{bse,t}}+\overline{\mathrm{Q}^{aFRR^{up}}_{bse,t}}-\mathrm{s}_{bse,t}\\&\leq 0\cdot\overline{\mathrm{u}^{syn}_{bse,t}}+\mathrm{P}^{soak}_{bse,t}+\mathrm{P}^{des}_{bse,t}+\mathrm{P}^{max}_{bse,t}\cdot\overline{\mathrm{u}^{disp}_{bse,t}}+(\mathrm{P}^{\min}_{bse,t}-\mathrm{P}^{max}_{bse,t})\cdot\overline{z_{bse,t+\mathrm{T_{bse}}}} \qquad \forall bse\in \mathrm{BSE}, t\in \mathrm{T}\end{aligned} \tag{3}$$

$$\begin{aligned}&\mathrm{MS}_{bse,t}-\mathrm{mFRR}^{dn}_{bse,t}-\overline{\mathrm{rr}^{dn}_{bse,t}}-\overline{\mathrm{s}^{\mathrm{rr}}_{bse,t}}-\overline{\mathrm{Q}^{aFRR^{dn}}_{bse,t}}+\mathrm{d}_{bse,t}\\&\geq 0\cdot\overline{\mathrm{u}^{syn}_{bse,t}}+\mathrm{P}^{soak}_{bse,t}+\mathrm{P}^{des}_{bse,t}+\mathrm{P}^{\min}_{bse,t}\cdot\left(\overline{\mathrm{u}^{disp}_{bse,t}}-\overline{\mathrm{u}^{AGC}_{bse,t}}\right)+\mathrm{P}^{AGC^{\min}}_{bse,t}\cdot\overline{\mathrm{u}^{AGC}_{bse,t}} \qquad \forall bse\in \mathrm{BSE}, t\in \mathrm{T}\end{aligned} \tag{4}$$

$$\begin{aligned}&\mathrm{MS}_{bse,t}+\mathrm{mFRR}^{up}_{bse,t}+\overline{\mathrm{rr}^{up}_{bse,t}}+\overline{\mathrm{d}^{\mathrm{rr}}_{bse,t}}+\overline{\mathrm{Q}^{aFRR^{up}}_{bse,t}}-\mathrm{s}_{bse,t}\\&\leq 0\cdot\overline{\mathrm{u}^{syn}_{bse,t}}+\mathrm{P}^{soak}_{bse,t}+\mathrm{P}^{des}_{bse,t}+\mathrm{P}^{max}_{bse,t}\cdot\left(\overline{\mathrm{u}^{disp}_{bse,t}}-\overline{\mathrm{u}^{AGC}_{bse,t}}\right)+\mathrm{P}^{AGC^{max}}_{bse,t}\cdot\overline{\mathrm{u}^{AGC}_{bse,t}} \qquad \forall bse\in \mathrm{BSE}, t\in \mathrm{T}\end{aligned} \tag{5}$$

Constraints (6) and (7) maximize the upward and downward mFRR BE that can be offered by a BSP in a given RTU, so as to respect its ramp-rate limits. In both constraints, the already activated RR BE in the respective direction is also considered.

$$\begin{aligned} & \mathrm{MS}_{bse,t} + \mathrm{mFRR}^{up}_{bse,t} + \overline{\mathrm{rr}^{up}_{bse,t}} + \overline{\mathrm{d}^{\mathrm{rr}}_{bse,t}} - \mathrm{IN}_{bse} - \mathrm{s}_{bse,t} \\ & \leq \mathrm{t} \cdot 15 \cdot \mathrm{RU}_{bse} \cdot \overline{\mathrm{u}^{disp}_{bse,t}} + \mathrm{N} \cdot \left( \overline{\mathrm{u}^{syn}_{bse,t}} + \overline{\mathrm{u}^{soak}_{bse,t}} \right) \qquad \forall bse \in \mathrm{BSE}, t \in \mathrm{T} \end{aligned} \tag{6}$$

$$\begin{aligned} & \mathrm{IN}_{bse} - \left( \mathrm{MS}_{bse,t} - \mathrm{mFRR}^{dn}_{bse,t} - \overline{\mathrm{rr}^{dn}_{bse,t}} - \overline{\mathrm{s}^{\mathrm{rr}}_{bse,t}} \right) - \mathrm{d}_{bse,t} \\ & \leq \mathrm{t} \cdot 15 \cdot \mathrm{RD}_{bse} \cdot \overline{\mathrm{u}^{disp}_{bse,t}} + \mathrm{N} \cdot \left( \overline{\mathrm{z}_{bse,t}} + \overline{\mathrm{u}^{des}_{bse,t}} \right) \qquad \forall bse \in \mathrm{BSE}, t \in \mathrm{T} \end{aligned} \tag{7}$$

Constraints (8) and (11) are included in the mFRR BEOs conversion process to limit the offered mFRR BE by a BSP in a preceding RTU, if this is required by the already awarded FCR and aFRR reserve quantities in the following RTU.

$$\begin{aligned} & \mathrm{MS}_{bse,t} - \mathrm{mFRR}^{dn}_{bse,t} - \overline{\mathrm{rr}^{dn}_{bse,t}} - \overline{\mathrm{s}^{\mathrm{rr}}_{bse,t}} + 15 \cdot \mathrm{RU}_{bse} + \mathrm{d}_{bse,t} \\ & \geq \mathrm{P}^{\min}_{bse,t+1} + \overline{\mathrm{Q}^{FCR^{dn}}_{bse,t+1}} + \overline{\mathrm{Q}^{aFRR^{dn}}_{bse,t+1}} \qquad \forall bse \in \mathrm{BSE}, t \in \mathrm{T} \end{aligned} \tag{8}$$

$$\begin{aligned} & \mathrm{MS}_{bse,t} + \mathrm{mFRR}^{up}_{bse,t} + \overline{\mathrm{rr}^{up}_{bse,t}} + \overline{\mathrm{d}^{\mathrm{rr}}_{bse,t}} - 15 \cdot \mathrm{RD}_{bse} - \mathrm{s}_{bse,t} \\ & \leq \mathrm{P}^{max}_{bse,t+1} - \overline{\mathrm{Q}^{FCR^{up}}_{bse,t+1}} - \overline{\mathrm{Q}^{aFRR^{up}}_{bse,t+1}} \qquad \forall bse \in \mathrm{BSE}, t \in \mathrm{T} \end{aligned} \tag{9}$$

$$\begin{aligned} & \mathrm{MS}_{bse,t} - \mathrm{mFRR}^{dn}_{bse,t} - \overline{\mathrm{rr}^{dn}_{bse,t}} - \overline{\mathrm{s}^{\mathrm{rr}}_{bse,t}} + 15 \cdot \mathrm{RU}_{bse} + \mathrm{d}_{bse,t} \\ & \geq \mathrm{P}^{\min}_{bse,t+1} \cdot \left( 1 - \overline{\mathrm{u}^{AGC}_{bse,t+1}} \right) + \mathrm{P}^{AGC^{\min}}_{bse,t+1} \cdot \overline{\mathrm{u}^{AGC}_{bse,t+1}} + \overline{\mathrm{Q}^{aFRR^{dn}}_{bse,t+1}} \qquad \forall bse \in \mathrm{BSE}, t \in \mathrm{T} \end{aligned} \tag{10}$$

$$\begin{aligned} & \mathrm{MS}_{bse,t} + \mathrm{mFRR}^{up}_{bse,t} + \overline{\mathrm{rr}^{up}_{bse,t}} + \overline{\mathrm{d}^{\mathrm{rr}}_{bse,t}} - 15 \cdot \mathrm{RD}_{bse} - \mathrm{s}_{bse,t} \\ & \leq \mathrm{P}^{max}_{bse,t+1} \cdot \left( 1 - \overline{\mathrm{u}^{AGC}_{bse,t+1}} \right) + \mathrm{P}^{AGC^{max}}_{bse,t+1} \cdot \overline{\mathrm{u}^{AGC}_{bse,t+1}} - \overline{\mathrm{Q}^{aFRR^{up}}_{bse,t+1}} \qquad \forall bse \in \mathrm{BSE}, t \in \mathrm{T} \end{aligned} \tag{11}$$

It is important to note that in constraints (2)–(11), overlined parameters constitute results from processes that have taken place before the mFRR BE conversion process, namely from the ISP [26] and from the RR BE clearing process [23]. More specifically, the ISP provides all commitments decisions and reserve awards, whereas the RR BE clearing provides the respective activated BE (including mandatory activations) activated from the RR.

The optimization problem of the mFRR BEOs conversion process constitutes a linear programming (LP) model that can be solved using commercial solvers.

Figure 4 below schematically summarizes the concept and the flow of the mFRR BE conversion process. More specifically, the red dashed box expresses the initial mFRR BEO submitted by a BSP to its local TSO (this is the part remaining after the participation in the forward/spot markets and the RR BE clearing process). After the execution of the mFRR BE conversion process, the TSO calculates the maximum mFRR BEO that can be submitted to the mFRR BE clearing platform. It is noted that under certain conditions, the TSO may activate a part of the maximum BEO quantity mandatorily/manually, prior to the mFRR BE clearing process, in order to attain feasible schedules for the BSPs. These conditions refer to meeting the technical/operating constraints (technical limits, ramp-rates, reserve awards etc.) of the conventional generating units.

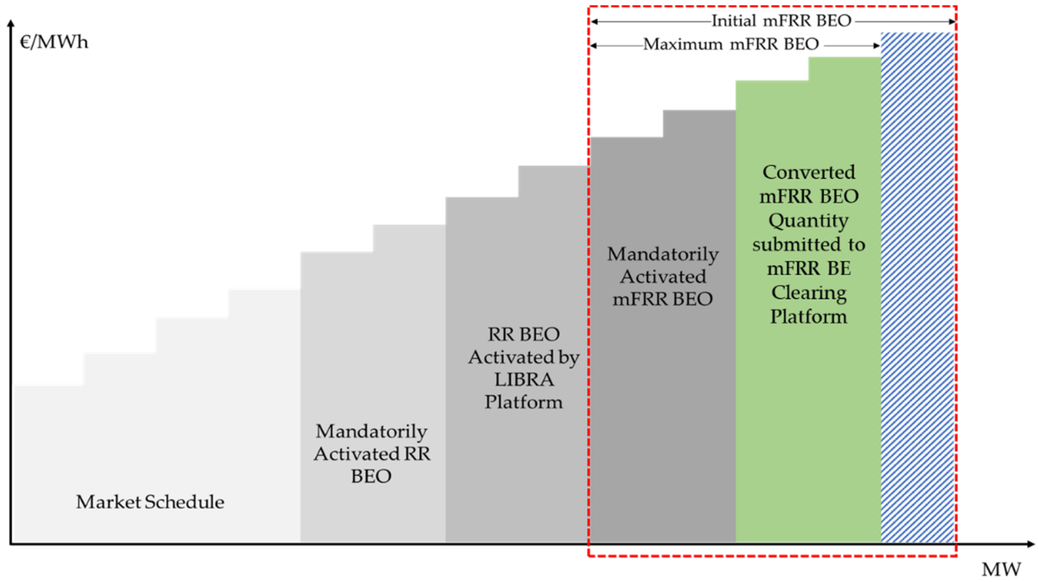


**Figure 4.** Conversion of an upward mFRR BEO before its insertion in the mFRR BE clearing model.

## 5. Manual Frequency Restoration Reserve Balancing Energy (mFRR BE) Clearing Model

This section elaborates on the mathematical formulation (objective function and constraints) of the mFRR BE clearing model, along with the solution methodology applied for the derivation of the respective results.

### 5.1. Mathematical Formulation

This sub-section presents in detail the mathematical modeling of the clearing model of the mFRR BE clearing platform, taking into consideration the "standard products", i.e., the standard types/formats of orders presented in Section 3, as well as other constraints imposed by TSOs [8]. Since the modeling framework includes both continuous and binary variables (as analytically described in the following sub-sections), the mFRR BE clearing problem is formulated as a mixed integer linear programming (MILP) model.

#### 5.1.1. Objective Function

The objective of the mFRR BE clearing model targets the maximization of the overall social welfare, by clearing the buying curve (demand) against the selling curve (supply). The buying curve comprises the positive imbalance needs (upward TSO needs/system shortage) and the downward BEOs submitted by the BSPs, whereas the selling curve includes the negative imbalance needs (downward TSO needs/system surplus) and the upward BEOs submitted by the BSPs.

The objective function is mathematically formulated, as shown in Equation (12). Parameter D equals 0.25 to account for the quarterly RTU.

$$\mathrm{MaxTW} = \mathrm{D}\cdot\left(\begin{array}{l} -\sum\limits_{or_{BSP}\in\ \mathrm{OR}^{\mathrm{up}}_{\mathrm{BSP}}}\ \sum\limits_{t\ \in \mathrm{T}}\left(\mathrm{P}^{or_{BSP}}_{up,t}\cdot \mathrm{Q}^{or_{BSP}}_{up,t}\cdot \mathrm{x}^{or_{BSP}}_{up,t}\right) - \sum\limits_{or_{BSP}\in\ \mathrm{OR}^{\mathrm{up}}_{\mathrm{BSP}}}\ \sum\limits_{t\ \in \mathrm{T}}\left(\mathrm{P}_{\mathrm{par}\,up,t}^{\ or_{BSP}}\cdot \mathrm{Q}_{\mathrm{par}\,up,t}^{\ or_{BSP}}\cdot \mathrm{x}_{\mathrm{par}\,up,t}^{\ or_{BSP}}\right) - \\ \sum\limits_{or_{BSP}\in\ \mathrm{OR}^{\mathrm{up}}_{\mathrm{BSP}}}\ \sum\limits_{t\ \in \mathrm{T}}\left(\mathrm{P}_{\mathrm{ch}\,up,t}^{\ or_{BSP}}\cdot \mathrm{Q}_{\mathrm{ch}\,up,t}^{\ or_{BSP}}\cdot \mathrm{x}_{\mathrm{ch}\,up,t}^{\ or_{BSP}}\right) - \sum\limits_{or_{BSE}\in\ \mathrm{OR}^{\mathrm{up}}_{\mathrm{BSE}}}\ \sum\limits_{t\in\ \mathrm{T}}\left(\mathrm{P}^{or_{BSE}}_{up,t}\cdot \mathrm{q}^{or_{BSE}}_{up,t}\right) - \\ \sum\limits_{or_{TSO}\in\ \mathrm{OR}^{\mathrm{dn}}_{\mathrm{TSO}}}\ \sum\limits_{t\ \in \mathrm{T}}\left(\mathrm{P}^{or_{TSO}}_{dn,t}\cdot \mathrm{Q}^{or_{TSO}}_{dn,t}\cdot \mathrm{n}^{or_{TSO}}_{dn,t}\right) + \sum\limits_{or_{BSP}\in\ \mathrm{OR}^{\mathrm{dn}}_{\mathrm{BSP}}}\ \sum\limits_{t\ \in \mathrm{T}}\left(\mathrm{P}^{or_{BSP}}_{dn,t}\cdot \mathrm{Q}^{or_{BSP}}_{dn,t}\cdot \mathrm{x}^{or_{BSP}}_{dn,t}\right) + \\ \sum\limits_{or_{BSP}\in\ \mathrm{OR}^{\mathrm{dn}}_{\mathrm{BSP}}}\ \sum\limits_{t\ \in \mathrm{T}}\left(\mathrm{P}_{\mathrm{par}\,dn,t}^{\ or_{BSP}}\cdot \mathrm{Q}_{\mathrm{par}\,dn,t}^{\ or_{BSP}}\cdot \mathrm{x}_{\mathrm{par}\,dn,t}^{\ or_{BSP}}\right) + \sum\limits_{or_{BSP}\in\ \mathrm{OR}^{\mathrm{dn}}_{\mathrm{BSP}}}\ \sum\limits_{t\ \in \mathrm{T}}\left(\mathrm{P}_{\mathrm{ch}\,dn,t}^{\ or_{BSP}}\cdot \mathrm{Q}_{\mathrm{ch}\,dn,t}^{\ or_{BSP}}\cdot \mathrm{x}_{\mathrm{ch}\,dn,t}^{\ or_{BSP}}\right) + \\ \sum\limits_{or_{BSE}\in\ \mathrm{OR}^{\mathrm{dn}}_{\mathrm{BSE}}}\ \sum\limits_{t\in\ \mathrm{T}}\left(\mathrm{P}^{or_{BSE}}_{dn,t}\cdot \mathrm{q}^{or_{BSE}}_{dn,t}\right) + \sum\limits_{or_{TSO}\in\ \mathrm{OR}^{\mathrm{up}}_{\mathrm{TSO}}}\ \sum\limits_{t\ \in \mathrm{T}}\left(\mathrm{P}^{or_{TSO}}_{up,t}\cdot \mathrm{Q}^{or_{TSO}}_{up,t}\cdot \mathrm{n}^{or_{TSO}}_{up,t}\right) \end{array}\right) \quad (12)$$

The set $t$ can be omitted from all of the symbols presented in the herein described formulation (objective function and constraints) since the model concerns a single-period optimization. However, again (as also stated in Section 4) it has been retained for homogeneity purposes.

#### 5.1.2. Order Clearing Constraints

Constraints (13)–(32) model the clearing rules of all of the order types provisioned in the respective implementation framework for the mFRR BE clearing platform [8]. More precisely, constraints (13)–(15) concern the maximum acceptance ratio of fully divisible, divisible and indivisible orders. Constraint (16) corresponds to the minimum acceptance ratio only for the case of divisible orders.

$$\mathrm{x}_{dr,t}^{fd} \leq 1 \qquad \forall\ fd \in \mathrm{FD},\ dr \in \mathrm{DR},\ t \in \mathrm{T} \tag{13}$$

$$\mathrm{x}_{dr,t}^{d} \leq \mathrm{u}_{dr,t}^{d} \qquad \forall d \in \mathrm{D},\ dr \in \mathrm{DR},\ t \in \mathrm{T} \tag{14}$$

$$\mathrm{x}_{dr,t}^{i} = \mathrm{u}_{dr,t}^{i} \qquad \forall i \in \mathrm{I},\ dr \in \mathrm{DR},\ t \in \mathrm{T} \tag{15}$$

$$\mathrm{x}_{dr,t}^{d} \geq \mathrm{MAR}_{dr,t}^{d} \cdot\ u_{dr,t}^{d} \qquad \forall d \in \mathrm{D},\ dr \in \mathrm{DR},\ t \in \mathrm{T} \tag{16}$$

Constraints (17)–(24) are incorporated in order to model the clearing conditions of the exclusive in volume orders. These type of orders can be further differentiated to fully divisible, divisible or indivisible. Constraints (23)–(24) cover the condition that the acceptance of an order belonging to a group of exclusive orders leads to the rejection of the other orders belonging to the same group.

$$\mathrm{x}_{dr,t}^{evfd} \leq \mathrm{o}_{dr}^{evfd} \qquad \forall evfd \in \mathrm{EVFD},\ dr \in \mathrm{DR},\ t \in \mathrm{T} \tag{17}$$

$$\mathrm{x}_{dr,t}^{evd} \leq o_{dr}^{evd} \qquad \forall evd \in \mathrm{EVD},\ dr \in \mathrm{DR},\ t \in \mathrm{T} \tag{18}$$

$$\mathrm{x}_{dr,t}^{evi} = u_{dr,t}^{evi} \qquad \forall evi \in \mathrm{EVI},\ dr \in \mathrm{DR},\ t \in \mathrm{T} \tag{19}$$

$$\mathrm{u}_{dr,t}^{evi} \leq o_{dr}^{evi} \qquad \forall evi \in \mathrm{EVI},\ dr \in \mathrm{DR},\ t \in \mathrm{T} \tag{20}$$

$$\mathrm{x}_{dr,t}^{evd} \geq \mathrm{MAR}_{dr,t}^{evd} \cdot\ \mathrm{o}_{dr}^{evd} \qquad \forall evd \in \mathrm{EVD},\ dr \in \mathrm{DR},\ t \in \mathrm{T} \tag{21}$$

$$\sum_{evfd\ \in\ \mathrm{EVFD}^{\,g}} \mathrm{o}_{dr}^{evfd} \leq 1 \qquad \forall g \in \mathrm{G},\ dr \in \mathrm{DR} \tag{22}$$

$$\sum_{evd\ \in\ \mathrm{EVD}^{\,g}} \mathrm{o}_{dr}^{evd} \leq 1 \qquad \forall g \in \mathrm{G},\ dr \in \mathrm{DR} \tag{23}$$

$$\sum_{evi\ \in\ \mathrm{EVI}^{\,g}} \mathrm{o}_{dr}^{evi} \leq 1 \qquad \forall g \in \mathrm{G},\ dr \in \mathrm{DR} \tag{24}$$

Lastly, constraints (25)–(32) concern the clearing conditions of the multi-part or child–parent orders. Both the parent and child orders can be either divisible or indivisible. Constraints (31)–(32) satisfy the condition that a given child order can be activated only if its parent order is activated as well, not vice versa.

$$\mathrm{x_{par}}_{dr,t}^{mpd} \leq \mathrm{u_{par}}_{dr,t}^{mpd} \qquad \forall mpd \in \mathrm{MPD},\ dr \in \mathrm{DR},\ t \in \mathrm{T} \tag{25}$$

$$\mathrm{x_{par}}_{dr,t}^{mpi} = \mathrm{u_{par}}_{dr,t}^{mpi} \qquad \forall mpi \in \mathrm{MPI},\ dr \in \mathrm{DR},\ t \in \mathrm{T} \tag{26}$$

$$\mathrm{x_{par}}_{dr,t}^{mpd} \geq \mathrm{MAR_{par}}_{dr,t}^{mpd} \cdot\ \mathrm{u_{par}}_{dr,t}^{mpd} \qquad \forall mpd \in \mathrm{MPD},\ dr \in \mathrm{DR},\ t \in \mathrm{T} \tag{27}$$

$$\mathrm{x_{ch}}_{dr,t}^{mpd} \leq \mathrm{u_{ch}}_{dr,t}^{mpd} \qquad \forall mpd \in \mathrm{MPD},\ dr \in \mathrm{DR},\ t \in \mathrm{T} \tag{28}$$

$$\mathrm{x_{ch}}_{dr,t}^{mpi} = \mathrm{u_{ch}}_{dr,t}^{mpi} \qquad \forall mpi \in \mathrm{MPI},\ dr \in \mathrm{DR},\ t \in \mathrm{T} \tag{29}$$

$$\mathrm{x_{ch}}_{dr,t}^{mpd} \geq \mathrm{MAR_{ch}}_{dr,t}^{mpd} \cdot \mathrm{u_{ch}}_{dr,t}^{mpd} \qquad \forall mpd \in \mathrm{MPD},\ dr \in \mathrm{DR},\ t \in \mathrm{T} \tag{30}$$

$$\mathrm{x_{ch}}_{dr,t}^{mpd} \leq \mathrm{x_{par}}_{dr,t}^{mpd} \qquad \forall mpd \in \mathrm{MPD},\ dr \in \mathrm{DR},\ t \in \mathrm{T} \tag{31}$$

$$\mathrm{x_{ch}}_{dr,t}^{mpi} \leq \mathrm{x_{par}}_{dr,t}^{mpi} \qquad \forall mpi \in \mathrm{MPI},\ dr \in \mathrm{DR},\ t \in \mathrm{T} \tag{32}$$

#### 5.1.3. Power Balance Constraints

Constraint (33) presents the power balance equation for a control area *ca* in a specific RTU *t*, which implements a self-scheduling market scheme. Notably, the net position of the control area equals the commercial exchanges between this control area and all of the neighboring control areas, taking into account the possible losses in DC interconnections. In a similar way, (34) represents the respective power balance equation of a control area *ca* in RTU *t*, which applies a central-scheduling market scheme.

$$\begin{aligned}
&\sum_{or_{TSO} \in \mathrm{OR}_{\mathrm{TSO}}^{\mathrm{up,ca}}} \left[\left(\mathrm{n}_{up,t}^{or_{TSO}} \cdot \mathrm{Q}_{up,t}^{or_{TSO}}\right) + \mathrm{tol_band}_{up,t}^{or_{TSO}}\right] + \sum_{or_{BSP} \in \mathrm{OR}_{\mathrm{BSP}}^{\mathrm{dn,ca}}} \mathrm{x}_{dn,t}^{or_{BSP}} \cdot \mathrm{Q}_{dn,t}^{or_{BSP}} + \\
&\sum_{or_{BSP} \in \mathrm{OR}_{\mathrm{BSP}}^{\mathrm{dn,ca}}} \mathrm{x_{par}}_{dn,t}^{or_{BSP}} \cdot \mathrm{Q}_{dn,t}^{or_{BSP}} + \sum_{or_{BSP} \in \mathrm{OR}_{\mathrm{BSP}}^{\mathrm{dn,ca}}} \mathrm{x_{ch}}_{dn,t}^{or_{BSP}} \cdot \mathrm{Q}_{dn,t}^{or_{BSP}} - \\
&\sum_{or_{TSO} \in \mathrm{OR}_{\mathrm{TSO}}^{\mathrm{dn,ca}}} \left[\left(\mathrm{n}_{dn,t}^{or_{TSO}} \cdot \mathrm{Q}_{dn,t}^{or_{TSO}}\right) \mathrm{tol_band}_{dn,t}^{or_{TSO}}\right] - \sum_{or_{BSP} \in \mathrm{OR}_{\mathrm{BSP}}^{\mathrm{up,ca}}} \mathrm{x}_{up,t}^{or_{BSP}} \cdot \mathrm{Q}_{up,t}^{or_{BSP}} - \\
&\sum_{or_{BSP} \in \mathrm{OR}_{\mathrm{BSP}}^{\mathrm{up,ca}}} \mathrm{x_{par}}_{up,t}^{or_{BSP}} \cdot \mathrm{Q}_{up,t}^{or_{BSP}} - \sum_{or_{BSP} \in \mathrm{OR}_{\mathrm{BSP}}^{\mathrm{up,ca}}} \mathrm{x_{ch}}_{up,t}^{or_{BSP}} \cdot \mathrm{Q}_{up,t}^{or_{BSP}} = \\
&-\sum_{l \in \mathrm{L_{ac}}} \mathrm{z}_l^{bz} \cdot \mathrm{e}_t^l - \sum_{l \in \mathrm{L_{dc}}} \left[\varphi_l^{ca} \cdot \left(\mathrm{f}_{l,t}^{+} - (1-\lambda_l) \cdot \mathrm{f}_{l,t}^{-}\right)\right] + \sum_{l \in \mathrm{L_{dc}}} \left[\psi_l^{ca} \cdot \left((1-\lambda_l) \cdot \mathrm{f}_{l,t}^{+} - \mathrm{f}_{l,t}^{-}\right)\right] \qquad \forall ca \in \mathrm{CA_{ss}},\ t \in \mathrm{T}
\end{aligned} \tag{33}$$

$$\begin{aligned}
&\mathrm{Imb}_t^{ca} - \sum_{or_{BSE} \in \mathrm{OR}_{\mathrm{BSE}}^{\mathrm{up,ca}}} \left(\mathrm{q}_{up,t}^{or_{BSE}}\right) + \sum_{or_{BSE} \in \mathrm{OR}_{\mathrm{BSE}}^{\mathrm{dn,ca}}} \mathrm{q}_{dn,t}^{or_{BSE}} \\
&- \sum_{or_{BSE} \in \mathrm{OR}_{\mathrm{BSE}}^{\mathrm{up,ca}}} \left(\mathrm{M}_{up,t}^{or_{BSE}}\right) + \sum_{or_{BSE} \in \mathrm{OR}_{\mathrm{BSE}}^{\mathrm{dn,ca}}} \left(\mathrm{M}_{dn,t}^{or_{BSE}}\right) = \\
&-\sum_{l \in \mathrm{L_{ca}}} \mathrm{z}_l^{ca} \cdot \mathrm{e}_t^l - \sum_{l \in \mathrm{L_{dc}}} \left[\varphi_l^{ca} \cdot \left(\mathrm{f}_{l,t}^{+} - (1-\lambda_l) \cdot \mathrm{f}_{l,t}^{-}\right)\right] + \sum_{l \in \mathrm{L_{dc}}} \left[\psi_l^{ca} \cdot \left((1-\lambda_l) \cdot \mathrm{f}_{l,t}^{+} - \mathrm{f}_{l,t}^{-}\right)\right] \qquad \forall ca \in \mathrm{CA_{cs}},\ t \in \mathrm{T}
\end{aligned} \tag{34}$$

#### 5.1.4. Cross-Zonal Capacity Constraints

Constraints (35) and (36) model the limits of the transmission capacity for each interconnection in both directions, which are available after the clearing of the spot markets. In addition, it is assumed that this capacity is implicitly allocated to the participating BSPs.

$$\mathrm{CZC}_{l,t}^{-} \leq \mathrm{e}_t^l \leq \mathrm{CZC}_{l,t}^{+} \qquad \forall\ l \in \mathrm{L_{ac}},\ \ t \in \mathrm{T} \tag{35}$$

$$\mathrm{CZC}_{l,t}^{-} \leq \mathrm{f}_{l,t}^{+} - \mathrm{f}_{l,t}^{-} \leq \mathrm{CZC}_{l,t}^{+} \qquad \forall\ l \in \mathrm{L_{dc}},\ \ t \in \mathrm{T} \tag{36}$$

#### 5.1.5. Tolerance Band Constraints

Constraint (37) models the case of the tolerance band as it is provisioned in the respective implementation framework of the MARI project.

$$\mathrm{tol\_band}_{dr,t}^{or_{TSO}} \leq \mathrm{TOL\_BAND}_{dr,t}^{or_{TSO}} \qquad \forall dr \in \mathrm{DR},\ \ t \in \mathrm{T},\ \ or_{TSO} \in \mathrm{OR_{TSO}} \tag{37}$$

#### 5.1.6. Interconnection Controllability Constraints

Constraint (38) is included in order to cover the case when TSOs submit an interconnection controllability request in borders with DC interconnections.

$$\mathrm{IC}_{l,t}^{-} = \mathrm{f}_{l,t}^{+} - \mathrm{f}_{l,t}^{-} = \mathrm{IC}_{l,t}^{+} \qquad \forall\ l \in \mathrm{L_{dc}},\ \ t \in \mathrm{T} \tag{38}$$

### *5.2. Solution Methodology*

For the simulation of the AOF execution, the following steps are executed for each RTU of a dispatch day:

- Step 1: Conversion of the orders submitted in the central-scheduling control areas, by solving the optimization problem presented in Section 4. The converted mFRR BEOs are then inserted in the subsequent mFRR BE clearing process in Step 2.
- Step 2: Execution of the mFRR BE clearing process jointly for the control areas applying the self-scheduling and central-scheduling schemes, by solving the optimization problem described in Section 5.1, in order to acquire the clearing results (optimal cleared mFRR BE orders, BE clearing prices, CZCs covered by the cross-zonal BE exchanges).
- Step 3: Check for paradoxically accepted orders (PAOs): A check is carried out in order to remove PAOs from the order book. In case PAOs are identified, they are removed, and Step 2 is executed again with the remaining BE orders. In the case that no more PAOs are present, the iterative process is terminated.

The overall methodology employs an iterative process for attaining the optimal cleared mFRR BE orders, which maximize the overall welfare, while meeting all of the problem constraints without the presence of any PAOs.

## 6. Results

This Section provides the test case (input data, participating countries) used within the framework of this work, the attained results and some information regarding the performance of the proposed model.

### *6.1. Case Setup*

The mFRR BE clearing model is assessed using a test case incorporating twenty-five countries that actively participate in the MARI project (Austria—AT, Belgium—BE, Croatia—HR, Czech Republic—CZ, Denmark—DK, Estonia—EE, Finland—FI, France—FR, Hungary—HU, Germany—GE, Greece—GR, Italy—IT, Latvia—LV, Lithuania—LT, Norway—NO, Netherlands—NL, Portugal—PT, Poland—PL, Romania—RO, Slovak Republic—SK, Slovenia—SI, Spain—ES, Sweden—SE, Switzerland—CH and Great Britain—UK), as shown in Figure 5. More specifically, the countries in the blue color are considered implementing the self-scheduling scheme, whereas the countries in the yellow color are considered applying the central-scheduling market arrangements (meaning that the conversion process referred to in Step 1 of Section 5.2 and analytically presented in Section 4 is taking place before the mFRR BE clearing process). In addition, it is noted that although Italy constitutes a control area with six bidding zones, for simplicity reasons, in this paper, it has been regarded as one control area with one equivalent bidding zone for the submission of BEOs.

For the majority of control areas (mostly coinciding with countries, with the exception of Germany), the level of upward/downward TSO mFRR inelastic and elastic needs considered in this study has been taken from the European Network of Transmission System Operators for Electricity (ENTSO-E) Transparency Platform [27], while for other control areas the respective data from the official TSO websites has been gathered and used. In Germany, there are four control areas in one bidding zone, which coincides with the country. For simplicity reasons, in the test case prepared by the authors, the four control areas of Germany have been considered as one "equivalent" control area (named "Germany"), since according to reference [8], in Germany there are mFRR balancing borders between these LFC areas for which the available capacity is assumed not to limit the balancing energy exchanges determined by the AOF of the mFRR BE clearing process. More specifically, the mFRR cross-border capacity limits on these borders shall be set to a value that should not be reached as a result of realistic cross-border exchanges. Figure 6, below, presents for all of the countries the respective profiles of mFFR needs (both elastic and inelastic) used in this study. As shown, depending on the control area, a specific profile and the level of mFRR needs for each RTU (1–96) has been selected. The considered prices for elastic TSO needs have been artificially created by the authors, using the following logic: the prices for elastic upward TSO needs range between 70–150 EUR/MWh and for elastic downward TSO needs between 15–30 EUR/MWh. The tolerance band has been taken equal to 50 MW in both directions (upward for positive imbalances and downward for negative imbalances).


**Figure 5.** European control areas included in the herein described test case.

Additionally, all of the BEOs prices and quantities considered in this study have been artificially created by the authors, providing a range of 70–9999 EUR/MWh for upward BEOs (9999 EUR/MWh is the price cap already applicable in most European balancing markets) and −500 EUR/MWh up to 70 EUR/MWh for downward BEOs. The CZCs between the participating control areas have been calculated as the difference between the total net transmission capacity taken from ENTSO-E's Mid-term Adequacy Forecast (MAF) 2020 for the target year 2025 [28] and the total scheduled commercial exchanges have been taken from the ENTSO-E Transparency Platform [27] corresponding to a day in July 2021 (1st July). At this point, it is worth mentioning that in the test case of this work, it is assumed that the TSOs do not enforce DC interconnection controllability.

All of the BSPs from all of the involved countries submit 4250 BEOs (in both directions) in the mFRR BE clearing platform. This set of BEOs includes all order types available in the MARI project, as presented in Section 3. The minimum acceptance ratio (MAR) of upward/downward divisible BEOs has also been artificially selected to create an interesting case with all of the possible clearing results.

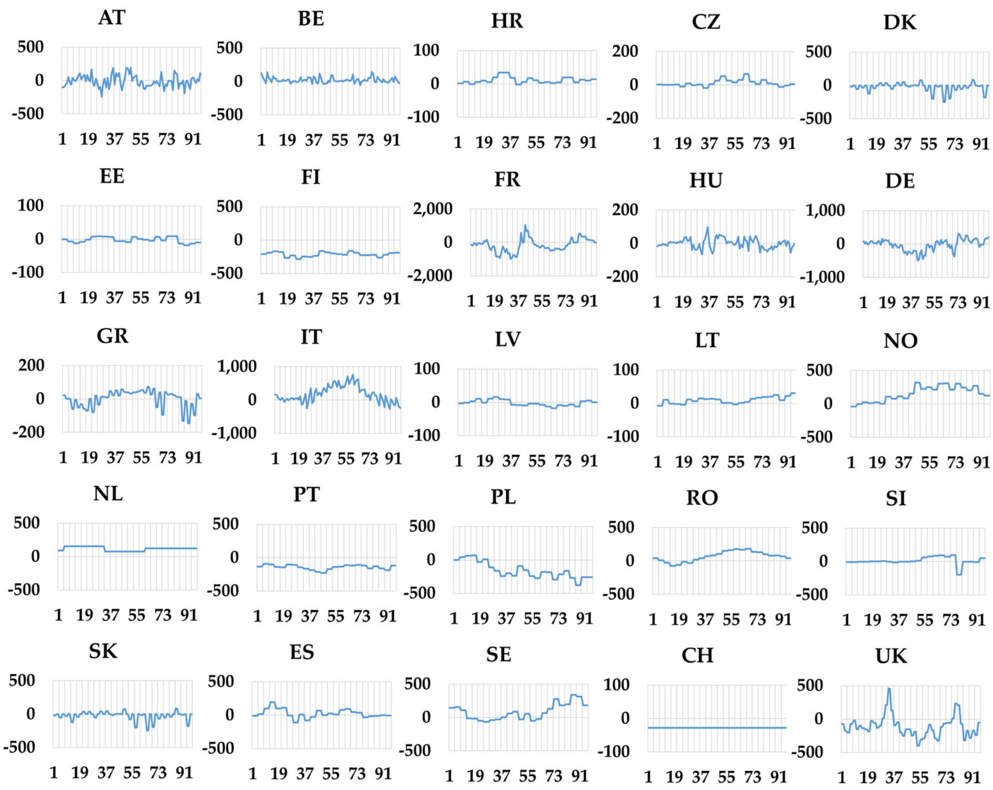


**Figure 6.** TSO mFRR needs in each participating control area included in the test case.

Finally, as stated in Section 4, initially, the conversion process for the BEOs of central-scheduling markets (Greece, Italy, Poland) is executed. This process adopts the results of the ISP (modeled as presented in [26]), which include the commitment decisions and the reserve awards of all balancing service entities (BSEs). The RR BEOs conversion process and the RR BE clearing (as in the TERRE project) follow. The attained results from these two procedures feed the mFRR quantity maximization model presented in Section 4, in order to set (a) the maximum/adjusted quantity of BEOs to be considered in the mFRR BE clearing platform, (b) the mFRR BE quantities to be mandatorily activated by the TSOs and (c) the quantities/prices of BEOs to be incorporated in the AOF clearing [25].

The complete dataset of this test case has been made publicly available by the authors [29] in order to be used as a reference for the reproduction of the herein demonstrated results by interested readers.

### 6.2. Test Results

This sub-section presents the attained results from the execution of the mFRR BE clearing process. Two distinct cases are considered, and their respective results are compared: (a) a case with zero CZCs expressing the current operation of balancing markets in European control areas, without any cross-zonal balancing exchange (hereinafter called "decoupled mode"), and (b) the case with non-zero CZCs expressing the ultimate target of fully operational cross-zonal balancing among the European control areas through the platform operating under the MARI project (hereinafter called "coupled mode").

As discussed in Section 4, before the mFRR BE clearing process, a conversion process for the BSEs of Greece, Italy and Poland is executed in order to attain the adjusted/maximum quantities of the respective BEOs. It is noted that in the herein presented test case, only generating units are considered as BSEs; nevertheless, the demand response and energy storage resources can also be easily incorporated in the conversion process. An example of this process is illustrated in Figure 7. We consider that the initial downward mFRR order submitted by a BSE (generating unit here) in Greece for the 10th RTU is equal to 120 MW. This BSE has a maximum power output of $P_{bse}^{max} = 450$ MW, the respective minimum level of production is $P_{bse}^{min} = 150$ MW and the market schedule, from its participation in the spot markets, is $MS_{bse,t} = 400$ MW. In addition, considering the results of the preceding ISP and RR BE clearing processes, a downward RR activation of $\overline{rr_{bse,t}^{dn}} = 97$ MW has been issued and $\overline{Q_{bse,t}^{aFRR^{dn}}} = 82$ MW for downward aFRR has been awarded, respectively, for this generating unit for the 10th RTU. Within this context, taking into consideration constraint (2) of Section 4, the mFRR quantity maximization model results in a maximum quantity of 71 MW, since the results of the preceding processes shall be respected, and thus, the final quantity of the BEO to be submitted from the Greek TSO to the mFRR BE clearing platform shall be 71 MW (cf. the initial quantity of the BEO, i.e., 120 MW). Figure 7 below schematically presents the concept of the conversion process for the above-described downward BEO.

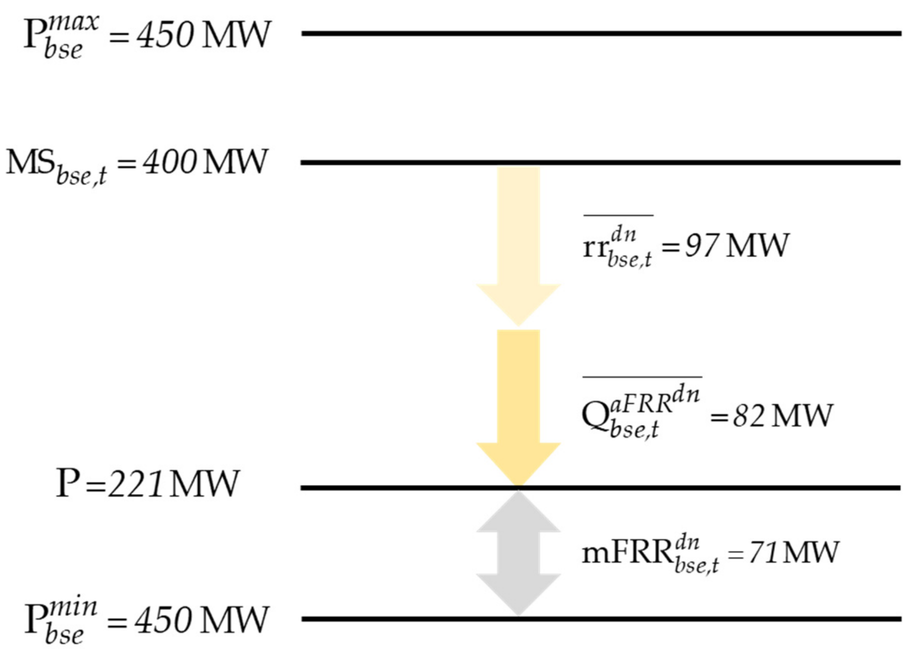


**Figure 7.** Conversion of downward BEO before submitting to the mFRR BE clearing platform.

Regarding the results of the mFRR BE clearing process, Figure 8 provides the market clearing prices (MCPs) in the two above-defined cases; as shown, in the decoupled mode, there are significant differences in the attained MCPs with large MCPs attained in several countries (e.g., Italy, Norway and Netherlands), whereas in the coupled mode there is a significant leveling of the attained MCPs at the level of 70–100 EUR/MWh in all of the countries. The most significant changes include the three above-stated countries (Italy, Norway and Netherlands), where the final attained MCPs are equal to 76.58 EUR/MWh (−80.80% compared to the initial MCP which is equal to 398.88 EUR/MWh), 76.68 EUR/MWh (−77.43% compared to the initial MCP which is equal to 339.77 EUR/MWh) and 76.58 EUR/MWh (−72.30% compared to the initial MCP which is equal to 276.45 EUR/MWh), respectively.

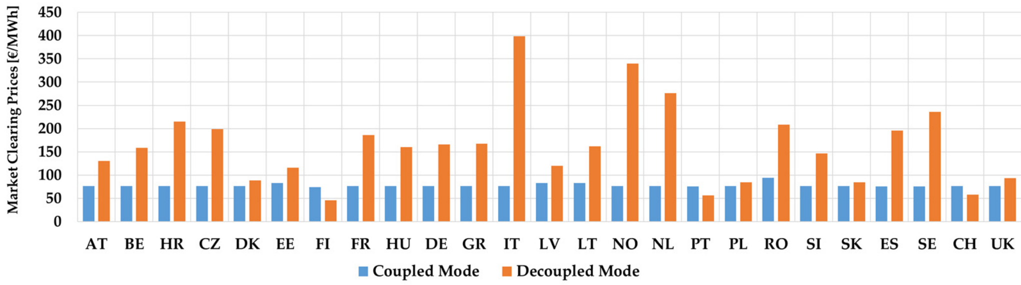


**Figure 8.** Market clearing prices attained for each participating control area.

Figure 9 provides the balancing costs calculated in each control area in the decoupled and coupled modes. As shown, the mFRR BE coupling process results in a significant reduction of the respective balancing cost for the majority of the involved control areas, i.e., the balancing cost of Italy, Norway, Netherlands and France presents the highest drop, whereas the balancing cost for Finland, Portugal and Switzerland slightly increases. Regarding the case of Italy, it is shown that its multiple interconnections with various neighboring countries facilitate much of the balancing process (in terms of resources that are eligible to be activated to reduce the balancing cost), and the balancing cost drops from EUR 2,338,500 to EUR −19,348 for a single day. Overall, the cross-zonal balancing of mFRR BE leads to a reduction in the balancing costs of EUR 7,196,712 for this single day.

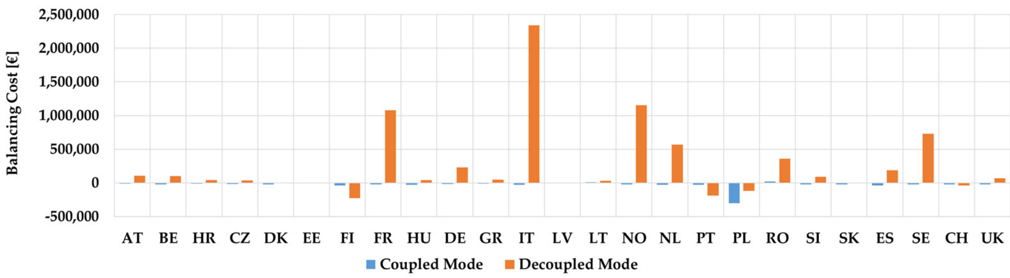


**Figure 9.** Balancing cost incurred in each participating control area.

Figure 10 illustrates the unitary change (increase/reduction) in the balancing cost of each control area stemming from its participation in the mFRR BE clearing process. In order to calculate such unitary change for each participating control area, we have divided the difference in the balancing cost (in EUR) between the decoupled and the coupled modes, with the respective system load. The system load concerns the 1st July 2021 and it has been downloaded from the ENTSO-E Transparency Platform [27]. As shown, in this test case in Norway, the unitary reduction reaches the level of 3.87 EUR/MWh, with the subsequent positive effects for the end-customers of the specific area depicted in their electricity tariffs. In some countries, there is a respective increase in the balancing costs, but overall, the cross-border balancing of mFRR BE leads to a weighted average unitary balancing cost reduction of 0.84 EUR/MWh.

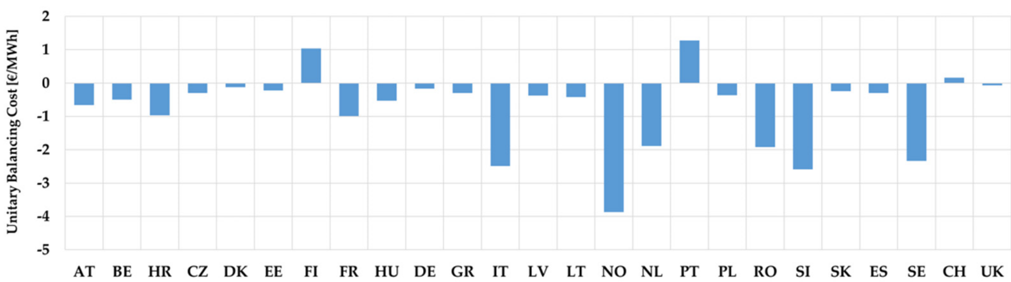


**Figure 10.** Unitary balancing cost of end-consumers in each participating control area.

Figures 11 and 12 depict for each participating control area the maximum and minimum prices of the activated upward BEOs, respectively. As shown, the maximum prices decrease greatly, whereas the minimum prices mostly remain stable at a level of approximately 70 EUR/MWh, as expected. This implies that in all of the countries, less expensive BEOs are activated in the coupled mode (cheaper BEOs of one control area cover the mFRR needs of neighboring control areas).

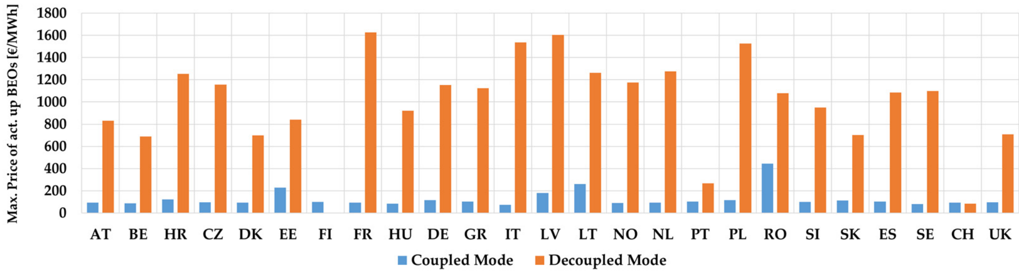


**Figure 11.** Maximum price of activated upward BEOs in each participating control area.

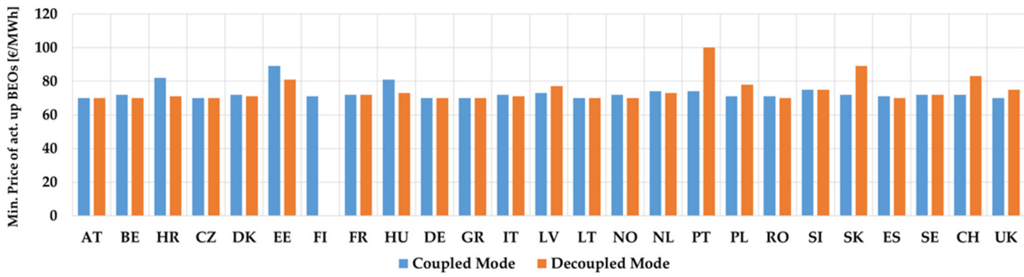


**Figure 12.** Minimum price of activated upward BEOs in each participating control area.

In the same vein, Figures 13 and 14 illustrate the maximum and minimum prices of the activated downward BEOs in each participating control area. As shown, the maximum prices are mostly identical in all of the countries in the decoupled and coupled modes, whereas the minimum prices increase in the coupled case at a level very close to the maximum prices.

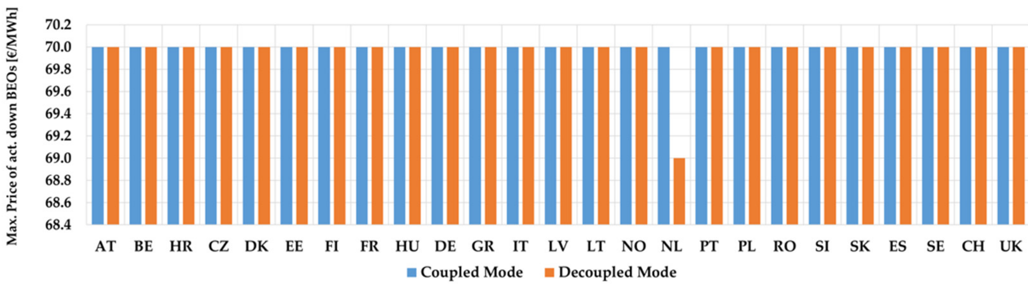


**Figure 13.** Maximum price of activated downward BEOs in each participating control area.

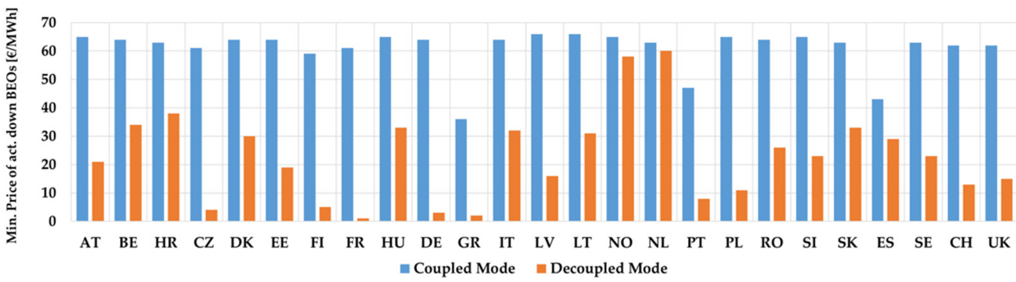


**Figure 14.** Minimum price of activated downward BEOs in each participating control area.

Moreover, Figures 15 and 16 present the amount of the activated upward and downward BE in each involved control area. In Figure 15, it is shown that the activated upward BE drops significantly in the coupled case since an imbalance netting is taking place implicitly in the mFRR BE clearing algorithm. In total, this imbalance netting results in an 86.87% reduction of the activated upward BE (total activated upward BE in the decoupled mode: 72,985 MWh, total activated upward BE in the coupled mode: 9585 MWh). The results are also similar in the downward direction presented in Figure 16. In total, the imbalance netting results in a 72.08% reduction of the activated downward BE (total activated upward BE in the decoupled mode: 107,483 MWh, total activated upward BE in the coupled mode: 30,007 MWh).

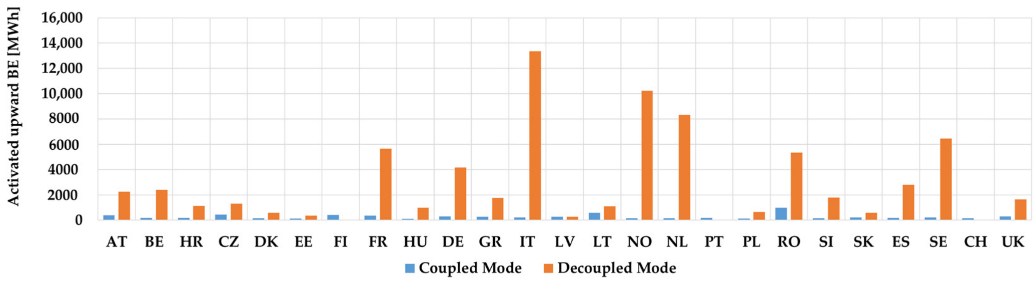


**Figure 15.** Activated upward BE in each participating control area.

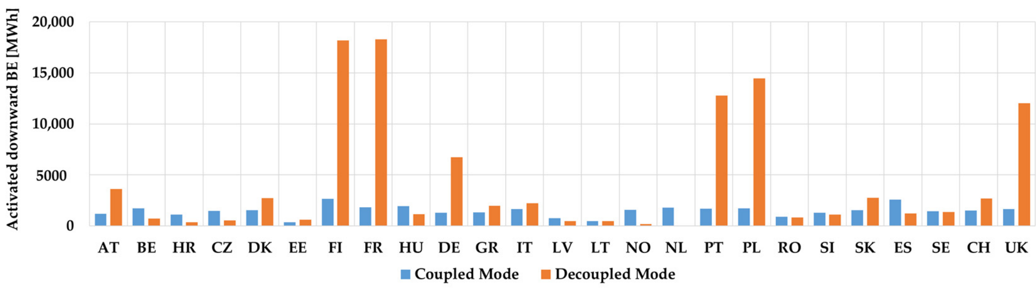


**Figure 16.** Activated downward BE in each participating control area.

Figure 17 below depicts the effect of the activation of the tolerance band constraint. As shown, the presence of the tolerance band submitted by the TSOs, along with their respective orders, leads to a balancing cost reduction of EUR 189,855.01 in the coupled mode, as compared to the respective balancing cost attained in the coupled mode without the tolerance band. This reduction can be attributed to the fact that in the case where the tolerance band constraint is active, more economical indivisible BEOs can be fully accepted, resulting in a lower overall balancing cost. When there is no tolerance band, these indivisible BEOs may be rejected, mainly in case of higher offered block quantities.

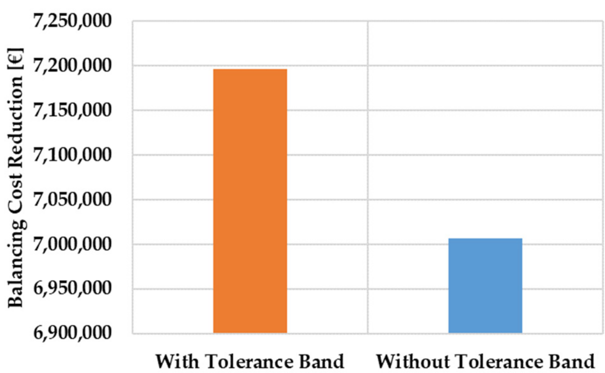


**Figure 17.** Balancing cost reduction when the tolerance band constraint is active.

For illustrations purposes, Figures 18 and 19 present the clearing results (power balance) of the Italian and French control areas for each RTU, respectively. These two control areas have been chosen since they have many interconnections (IT–AT, IT–FR, IT–GR, IT–SI, IT–CH and FR–DE, FR–IT, FR–CH, FR–BE, FR–ES) with countries participating in the MARI project and it is more easily and immediate to highlight the effect of the balancing market coupling.

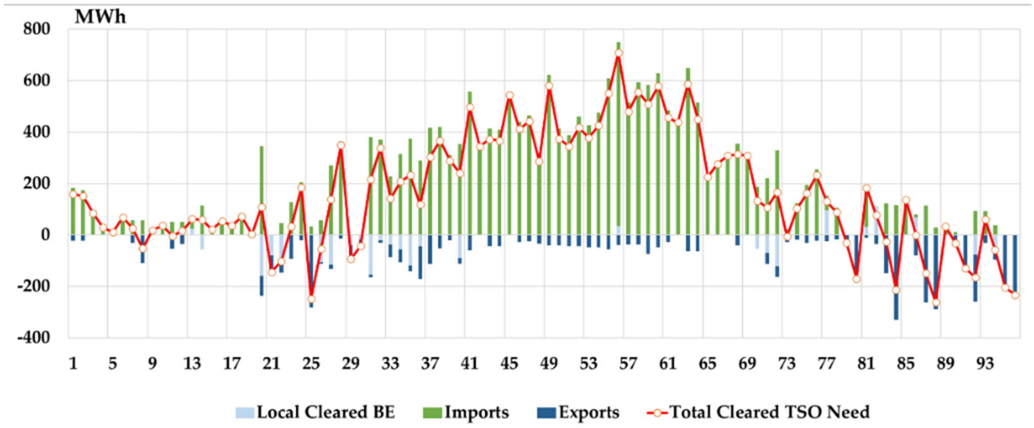


**Figure 18.** Power balance and cleared mFRR BE quantities per RTU for Italy.

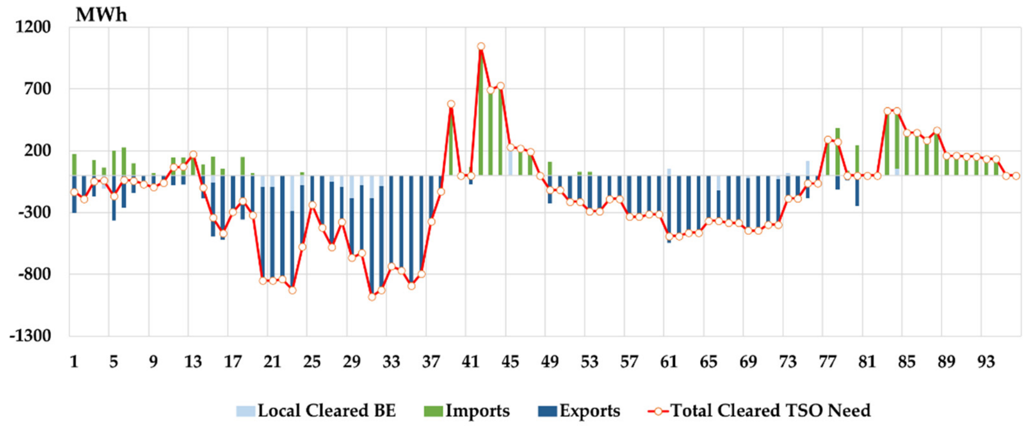


**Figure 19.** Power balance and cleared mFRR BE quantities per RTU for France.

Within this context, as shown in Figure 18, in RTUs 30–72, the Italian TSO covers its upward mFRR needs absolutely from imports (less expensive resources participate in the Italian balancing market), leading to almost zero BE activated from local BSPs. In addition, there are RTUs (e.g., RTU 20) where the Italian area imports—from neighboring countries—more mFRR BE quantities than required, and simultaneously exports mFRR BE quantities to other neighboring countries.

On the other hand, the French TSO has more downward mFRR needs during the selected dispatch day, and by participating in this mFRR BE clearing process in the coupled mode, it has the opportunity to export BE during many RTUs (14–38 and 49–76 in Figure 19) and not activate downward BE from local BSPs. In addition, the French TSO covers its minimal upward mFFR needs mainly by importing BE from neighboring countries (RTUs 39–48 and 77–96 in Figure 19), avoiding again the activation of upward BE from local BSPs.

In general, it is becoming apparent that the balancing market coupling can facilitate the balancing process in countries with high imbalance needs (e.g., Italy and France) and countries with limited interconnections (e.g., Portugal is interconnected only with Spain—Figure 20 below).

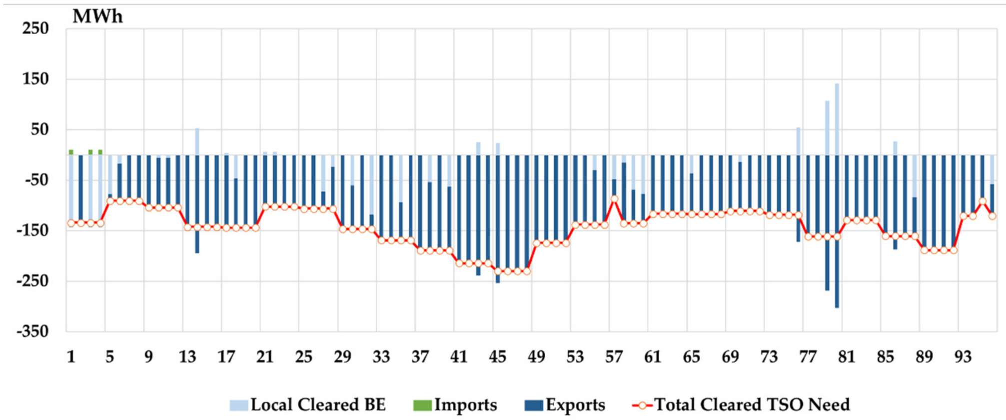


**Figure 20.** Power balance and cleared mFRR BE quantities per RTU for Portugal.

### 6.3. Computational Issues

The herein presented optimization models (BEOs conversion process and mFRR BE clearing model) have been solved on a desktop personal computer (PC) equipped using the general algebraic modeling system (GAMS) software [30] and the CPLEX 12.9 solver. Each quarter-hourly problem comprises 43,336 constraints with 3250 binary variables, 9821 continuous variables and 88,789 non-zero elements. The total processing time for the execution of the 96 RTUs (including the re-executions due to the presence of PAOs) reached 104 s.

## 7. Conclusions

In this paper, the authors presented the analytical mathematical formulation for the solution of the cross-border mFRR BE auctions. This framework fully complies with the requirements of the implementation framework [8] of the MARI project. Various studies in the literature have been conducted to analyze and highlight the potential benefits of the cross-border balancing in the European region. Such research works usually consider a simplified version of the modeling framework [14–18], ignoring many features of the MARI platform clearing model, such as the tolerance band and the interconnection controllability. Additionally, there is no research work handling the conversion process of the balancing energy orders in central-scheduling markets. The novelty of this work as compared to the existing literature lies mainly on the following contributions:

(a) The incorporation of all BEO types and the analytical presentation of the mathematical equations of their clearing conditions;
(b) The incorporation of both self-scheduling and central-scheduling systems in the same modeling framework; for the latter, a conversion process of the submitted BEOs is executed before the mFRR BE clearing process;
(c) The modeling of the conversion process for the preparation of the BEOs, before entering the mFRR BE clearing process;
(d) The modeling of interconnection controllability;
(e) The inclusion of elastic and inelastic orders defined appropriately by the TSOs;
(f) The consideration of the constraint concerning the tolerance band submitted by the participating TSOs.

A case study including twenty-five countries has been employed in order to evaluate the performance of the proposed models; the models' execution time indicates that the overall algorithm is computationally efficient. The attained clearing results indicate that a price convergence among the involved control areas is achieved from the cross-border exchange of mFRR BE. This can be explained by the fact that more economical resources belonging to one control area are requested to satisfy the mFRR balancing needs from neighboring control areas. In addition, the attained results highlight the significance of the imbalance netting that takes place during the joint the mFRR BE clearing process, which results in a rather crucial reduction in the balancing costs incurred by the participating TSOs. This reduction can also be deemed useful both for the balance responsible parties (BRPs) who pay fewer balancing costs to the TSOs, and ultimately for the end-consumers who enjoy lower electricity tariffs.

Finally, the authors believe that the presented model can be rather useful for both scientific researchers and business analysts since it constitutes the first work presenting the analytical mathematical formulation of the mFRR BE clearing model, in full compliance with the requirements of the European regulations. More specifically, TSOs applying the central-scheduling model and BSPs participating in markets with portfolio bidding can implement the conversion model described in Section 4. In addition, the clearing model presented in Section 5 can provide important insights for the modeling of the mFRR BE clearing platform.

The authors' future research will focus on the incorporation of constraints for both zonal and nodal systems, as well as constraints for the simulation of the flow-based approach. The inclusion of other types of resources, such as demand response and energy storage, could also be another enhancement of this work.

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**Conflicts of Interest:** The authors declare no conflict of interest.

## Abbreviations

| | |
|---|---|
| aFRR | automatic frequency restoration reserve |
| AGC | automatic generation control |
| AOF | activation optimization function |
| BE | balancing energy |
| BEO | balancing energy order |
| BRP | balance responsible party |
| BSE | balancing service entity |
| BSP | balance service provider |
| CMOL | common merit order list |
| CZC | cross-zonal capacity |
| DC | direct current |
| DP | delivery period |
| EBGL | Commission Regulation (EU) 2017/2195 of 23 November 2017 establishing a guideline on electricity balancing |
| ENTSO-E | European Network of Transmission System Operators for Electricity |
| FAT | full activation time |
| FCR | frequency containment reserve |
| IGCC | International Grid Control Cooperation |
| ISP | integrated scheduling process |
| LFC | load frequency control |
| LP | linear programming |
| mFRR | manual frequency restoration reserve |
| MAF | mid-term adequacy forecast |
| MAR | minimum acceptance ratio |
| MARI | Manually Activated Reserves Initiative |
| MCP | market clearing price |

| | |
|---|---|
| MILP | mixed integer linear programming |
| OCGT | open cycle gas turbine |
| PAO | paradoxically accepted order |
| PICASSO | Platform for the International Coordination of Automated Frequency Restoration and Stable System Operation |
| RR | replacement reserve |
| RTU | real-time unit |
| SO | Commission Regulation (EU) 2017/1485 of 2 August 2017 establishing a guideline on electricity transmission system operation |
| TERRE | Trans European Replacement Reserves Exchange |
| TSO | transmission system operator |

**Nomenclature**

*Sets and Indices*

| | |
|---|---|
| $t \in \mathrm{T}$ | Real-Time Units (RTUs) of mFRR BE clearing model horizon; $\mathrm{T} = \{1\}$ |
| $bse \in \mathrm{BSE}$ | Set of BSEs (only generating units from central-scheduling systems) submitting orders for the MARI platform |
| $or \in \mathrm{OR}$ | Set of BEOs submitted by BSPs/BSEs, where$\mathrm{OR} = \mathrm{FD} \cup \mathrm{D} \cup \mathrm{I} \cup \mathrm{EVFD} \cup \mathrm{EVD} \cup \mathrm{EVI} \cup \mathrm{MPD} \cup \mathrm{MPI}$ |
| $or_{TSO} \in \mathrm{OR_{TSO}}$ | Set of orders (inelastic and/or elastic) submitted by TSOs where $\mathrm{OR_{TSO}^{up}} \cup \mathrm{OR_{TSO}^{dn}} = \mathrm{OR_{TSO}} \subseteq \mathrm{OR}$ are the respective subsets of upward and downward TSO orders |
| $or_{BSP} \in \mathrm{OR_{BSP}}$ | Set of BEOs submitted by the BSPs of the self-scheduling markets, where $\mathrm{OR_{BSP}^{up}} \cup \mathrm{OR_{BSP}^{dn}} = \mathrm{OR_{BSP}} \subseteq \mathrm{OR}$ are the respective subsets of upward and downward BEOs |
| $or_{BSE} \in \mathrm{OR_{BSE}}$ | Set of BEOs submitted by BSPs of the central-scheduling markets per BSE, where $\mathrm{OR_{BSE}^{up}} \cup \mathrm{OR_{BSE}^{dn}} = \mathrm{OR_{BSE}} \subseteq \mathrm{OR}$ are the respective subsets of upward and downward BEOs |
| $ca \in \mathrm{CA}$ | Set of control areas, where $\mathrm{CA_{ss}} \cup \mathrm{CA_{cs}} = \mathrm{CA}$ are the respective subsets of the control areas applying the self-scheduling scheme and the central-scheduling scheme respectively |
| $dr \in \mathrm{DR}$ | Set for the direction of BEOs submitted by the TSO and the BSPs (upward or downward) |
| $l \in \mathrm{L}$ | Set of transmission lines, where $\mathrm{L_{ac}} \cup \mathrm{L_{dc}} = \mathrm{L}$ are the respective subsets of AC and DC transmission lines |
| $fd \in \mathrm{FD}$ | Set of the fully divisible BEOs submitted by BSPs |
| $d \in \mathrm{D}$ | Set of the divisible BEOs submitted by BSPs |
| $i \in \mathrm{I}$ | Set of the indivisible BEOs submitted by BSPs |
| $evfd \in \mathrm{EVFD}$ | Set of the exclusive in volume fully divisible BEOs submitted by BSPs |
| $evd \in \mathrm{EVD}$ | Set of the exclusive in volume divisible BEOs submitted by BSPs |
| $evi \in \mathrm{EVI}$ | Set of the exclusive in volume indivisible BEOs submitted by BSPs |
| $mpd \in \mathrm{MPD}$ | Set of the multi-part divisible BEOs submitted by BSPs |
| $mpi \in \mathrm{MPI}$ | Set of the multi-part indivisible BEOs submitted by BSPs |
| $g \in \mathrm{G}$ | Set of the exclusive in volume groups |

*Parameters*

| | |
|---|---|
| $\mathrm{P}_{dr,t}^{or}$ | Price of BEO *or* in direction *dr* in RTU *t* (€/MWh) |
| $\mathrm{Ppar}_{dr,t}^{or}$ | Price of parent BEO *or* in direction *dr* in RTU *t* (€/MWh) |
| $\mathrm{Pch}_{dr,t}^{or}$ | Price of child BEO *or* in direction *dr* in RTU *t* (€/MWh) |
| $\mathrm{P}_{dr,t}^{or_{BSE}}$ | Price of BEO $or_{BSE}$ in direction *dr* in RTU *t* (€/MWh) |
| $\mathrm{P}_{bse,t}^{c}$ | Technical limit of type c (*soak, des, min, max*, $AGC^{min}$, $AGC^{max}$) of BSE *bse* in RTU *t* (MW). |
| $\mathrm{Q}_{dr,t}^{or}$ | Quantity of BEO *or* in direction *dr* in RTU *t* (MW) |

| | |
|---|---|
| ${Q_{par}}_{dr,t}^{or}$ | Quantity of parent BEO *or* in direction *dr* in RTU *t* (MW) |
| ${Q_{ch}}_{dr,t}^{or}$ | Quantity of child BEO *or* in direction *dr* in RTU *t* (MW) |
| $Q_{dr,t}^{or_{BSE}}$ | Quantity of BEO $or_{BSE}$ in direction *dr* in RTU *t* (€/MWh) |
| $MAR_{dr,t}^{or}$ | Minimum Acceptance Ratio of BEO *or* in direction *dr* in RTU *t* (p.u.), where $or \in OR = D \cup EVD$ |
| ${MAR_{par}}_{dr,t}^{mpd}$ | Minimum Acceptance Ratio of parent BEO *mpd* in direction *dr* in RTU *t* (p.u.) |
| ${MAR_{ch}}_{dr,t}^{mpd}$ | Minimum Acceptance Ratio of child BEO *mpd* in direction *dr* in RTU *t* (p.u.) |
| $\varphi_l^{ca} / \psi_l^{ca}$ | Parameter indicating that DC transmission line *l* begins/ends from/to control area *ca*, if equal to 1; otherwise it is equal to 0 |
| $\overline{u_{bse,t}^{n}}$ | Commitment (binary) result taken from the solution of ISP; equal to 1 if BSE *bse* is in operating state *n* (*syn, soak, disp, des*) during RTU *t*. |
| $\overline{Q_{bse,t}^{r}}$ | Award of BSE *bse* in RTU *t* for reserve type *r* ($FCR^{up}$, $FCR^{dn}$, $aFRR^{up}$, $aFRR^{dn}$), taken from the solution of ISP (MW) |
| $MS_{bse,t}$ | Market schedule of BSE *bse* in RTU *t* (MW) |
| $RU/RD_{bse}$ | Ramp rate (up/down) of BSE *bse* (MW/min) |
| $\overline{rr_{bse,t}^{dr}}$ | RR activation by the TERRE platform of BSE *bse* in direction *dr* in RTU *t* (MW) |
| $\overline{d/s_{bse,t}^{rr}}$ | Manual RR activation by the TSO (in central-scheduling markets) of BSE *bse* in RTU *t* (MW) |
| $IN_{bse}$ | Initial power output of BSE *bse* in the mFRR Quantity Maximization Process [MW]. |
| $P_{bse,t}^{viol}$ | Penalty (non-physical) price for BSE's *bse* operating constraint violations during RTU *t* [€/MWh]. |
| $\lambda_l$ | Loss factor of DC transmission line *l* (%) |
| $CZC_{l,t}^{+/-}$ | Available CZC of transmission line *l* in RTU *t* (MW) in both directions (+ corresponds to the CZC from control area *ca* to control area *ca′* and − corresponds to the CZC from control area *ca′* to control area *ca*) |
| $TOL\_BAND_{dr,t}^{or_{TSO}}$ | Tolerance band of BEO $or_{TSO}$ in direction *dr* in RTU *t* (MW) |
| $IC_{l,t}^{+/-}$ | Intended flow of transmission line *l* in RTU *t* (MW) submitted by TSOs for controllability reasons (+ corresponds to the flow from control area *ca* to control area *ca′* and—corresponds to the flow from control area *ca′* to control area *ca*) |

*Variables*

| | |
|---|---|
| $mFRR_{bse,t}^{dr}$ | mFRR BEO of BSE *bse* in direction *dr* and RTU *t*, to be maximized during the mFRR Quantity Maximization Process [MW]. |
| $d/s_{bse,t}$ | Deficit / surplus of BSE *bse* in RTU *t*, denoting the mFRR BE to be manually activated by the TSOs [MW]. |
| $x_{dr,t}^{or}$ | Acceptance ratio of BEO *or* submitted by BSPs in direction *dr* and in RTU *t* |
| ${x_{par}}_{dr,t}^{or}$ | Acceptance ratio of parent BEO *or* submitted by BSPs in direction *dr* and in RTU *t* |
| ${x_{ch}}_{dr,t}^{or}$ | Acceptance ratio of child BEO *or* submitted by BSPs in direction *dr* and in RTU *t* |
| $n_{dr,t}^{or_{TSO}}$ | Acceptance ratio of BEO $or_{TSO}$ submitted by the TSO in direction *dr* and in RTU *t* |
| $u_{dr,t}^{d/i/evi}$ | Binary variable indicating if BEO $d/i/evi$ is activated in direction *dr* in RTU *t* |

| | |
|---|---|
| $\mathrm{upar}_{dr,t}^{mpd/mpi}$ | Binary variable indicating if parent BEO *mpd*/*mpi* is activated in direction *dr* in RTU *t* |
| $\mathrm{uch}_{dr,t}^{mpd/mpi}$ | Binary variable indicating if child BEO *mpd*/*mpi* is activated in direction *dr* in RTU *t* |
| $o_{dr}^{or}$ | Binary variable indicating if BEO *or* is activated in direction *dr* where or $\in$ OR = EVFD $\cup$ EVD $\cup$ EVI |
| $e_t^l$ | BE exchange in transmission line *l* in RTU *t* (MW) |
| $f_{l,t}^{+/-}$ | Positive variables used in the power flow variable decomposition schema for DC transmission line *l* in RTU *t* (MW) (+ corresponds to the flow from control area *ca* to control area *ca'* and—corresponds to the flow from control area *ca'* to control area *ca*) |
| $q_{dr,t}^{or_{BSE}}$ | Cleared quantity of BEO $or_{BSE}$ in direction *dr* in RTU *t* (MW) |
| $\mathrm{tol\_band}_{dr,t}^{or_{TSO}}$ | Cleared tolerance band of BEO $or_{TSO}$ in direction *dr* in RTU *t* (MW) |

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