Hierarchical Balancing in Zonal Markets

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***Abstract*—Balancing is becoming increasingly coordinated in Europe with the rollout of cross-zonal platforms for the activation of reserve. The European balancing platforms that are being put in place employ zonal network models. The misrepresentation of network constraints in these balancing platforms may cause congestion, which would be challenging to address very close to real time. We propose a hierarchical implementation of nodal balancing which respects the zonal design of European balancing platforms. We illustrate our approach on the classic six-node Chao-Peck example, and discuss the compatibility of our proposal with the institutional requirements of European balancing markets.**

I. INTRODUCTION

The integration of balancing operations in Europe is advancing rapidly. The launch of integrated market clearing platforms in the coming years provides evidence of this evolution. These include (i) "TERRE", the platform for the activation of replacement reserve, (ii) "MARI", the platform for the activation of manual frequency restoration reserve (abbreviated mFRR) [7], (iii) "PICASSO", the platform for the activation of automatic frequency restoration reserve (abbreviated aFRR), and (iv) "IGCC", the platform for the activation of frequency containment reserve (FCR). Note that these platforms are relevant to the *activation* of balancing energy (as opposed to the auctioning of reserve capacity). This integration is a necessary step for power system operations in a regime of large-scale renewable energy integration.

One significant weakness of the balancing platforms that are being put in place is the poor representation of the physical laws that govern power flow. The focus in this paper is on the integrated platform for tertiary reserve activation, MARI. In MARI, which will be going live in the following years [1] (see also article 20.6 of [8]), the network is approximated using an ATC transportation-based model. Future versions of the platform may incorporate a flow-based zonal network model.

A. Weaknesses of Zonal Market Clearing

The inability of transportation-based ATC models to represent power flows accurately is well-documented in the literature [6]. Recent research [3] suggests that flow-based zonal market coupling models fail to overcome the weaknesses of ATC-based models.

Zonal market clearing creates a host of issues in electricity market and system operations, including (i) operational inefficiencies, (ii) gaming opportunities, (iii) distortions to long-term investment signals, and (iv) difficulties in maintaining operational security. We comment briefly on the first three aspects, and expand in the remainder of the paper on item (iv).

Operational inefficiencies in zonal market clearing result from the tendency of zonal models to clear in merit order within a zone, without regards to internal congestion patterns. When committing resources with low variable cost within a zone, the resulting network violations must then be corrected by starting up costly flexible resources [4]. In the process, one incurs the startup cost of the flexible resources, as well as the minimum load cost of the cheap resources that are wrongly committed due to zonal market clearing. This induces a very significant cost for redispatch, which can be avoided in nodal market clearing. The cost of redispatch amounted to approximately a billion euro in 2017, in Germany alone [14].

Gaming opportunities emerge in zonal market clearing models followed by redispatch through INC-DEC gaming [2], [11]. The exercise of INC-DEC gaming, which was one of the major pitfalls of the pre-2001 California design, is a strategy that can be applied whether or not an agent is in a position to exercise market power [9]. This has motivated the application of cost-based redispatch in certain European markets of Central Western Europe, including Germany.

The lack of a spatially granular locational price signal obviates the appropriate placement of generation and demand resources in zonal markets [10]. The power system economics literature [5] establishes the optimal expansion problem as the basis for deriving prices that signal optimal investment in the system. The original argument can be extended to the case of transmission constraints. Deviations from the fundamental physical model of the transportation network tend to distort price signals, and raise challenges in locating resources at the parts of the grid where they are needed most.

The present paper is focused on the fact that a zonal balancing market model may result in balancing actions which may violate transmission constraints in highly meshed networks. Since balancing takes place very close to real time, there is little if any time left for correcting these network violations after balancing resources have been activated. Consequently, this approach threatens security of supply, unless significant "headroom" is kept available in the grid, which is inefficient as it leas to under-utilization.

B. Paper Contribution

In order to address the problem of network violations in zonal balancing, we propose a hierarchical approach for incorporating nodal network constraints to a zonal market clearing model. The content of the paper is based on work performed by the authors on behalf of Statnett, the Norwegian TSO, in which multiple approaches have been studied in order to address the congestion that could be caused by MARI activations on the Norwegian grid. We therefore focus on the balancing platform for tertiary reserve, MARI, for the remainder of the paper. Our approach is inspired by hierarchical TSO-DSO coordination schemes [12].

The key idea of our approach is that a TSO can aggregate the offers of its domestic balancing service providers (BSPs) to an "aggregate BSP" offer, which is cleared in MARI. The net position of the zone is then disaggregated to individual BSPs by the TSO, using a nodal model. This hierarchical aggregation / disaggregation step aims at respecting the institutional constraints of MARI, while allowing a TSO to avoid network violations within its network when participating in international balancing.

In Section II we illustrate the problem that arises from balancing with a zonal model. In Section III we illustrate our proposal for hierarchical balancing on a concrete example. We discuss the implementation of our proposal in the context of European legislation in section IV. Section V concludes and discusses perspectives for future research.

II. Balancing with a Zonal Model

We consider the following sequence of events in our discussion: (i) A day-ahead zonal market clears. (ii) The schedules of individual resources (as opposed to the zonal positions) are fixed to the day-ahead outcome for the balancing stage. In the balancing stage, a subset of the resources are activated.

A. Day-Ahead Market Clearing

Throughout the paper, we consider a variant[1] of the Chao-Peck 6-node example [13]. The model consists of the supply functions that are described in Fig. 1. The 6-node network is partitioned into three zones: North, South-1 and South-2. We are concerned about congestions that can occur in the Northern zone as a result of participating in a coordinated balancing platform such as MARI.

The Chao Peck example has demand in nodes 3, 4, and 6. We assume that consumers behave as price takers (VOLL of 1000 €/MWh) in our analysis. On the demand side, we consider a commercially congested exchange scenario. According to this scenario, the demand in the Northern zone, South-1 zone and South-2 zone is 300 MW each.

The six-node network is partitioned into a North zone with cheap generation and two South zones with more expensive generation. We impose an ATC limit for the zonal model, with the following values[2]: 150 MW for link N-S1, 100 MW for link N-S2, and 62.5 MW for link S1-S2. This results in an export of power from the Northern zone to the Southern zones.

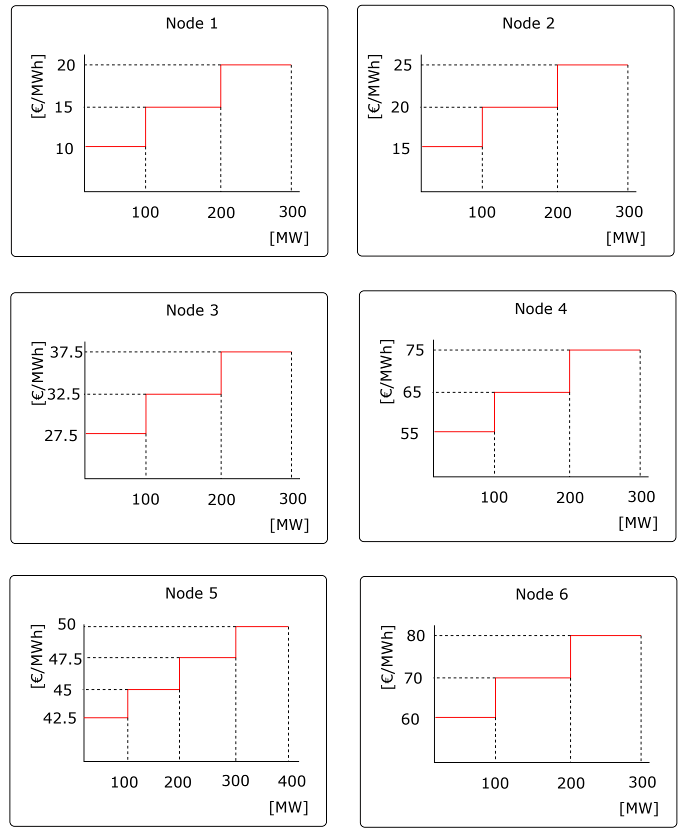

Fig. 1: Supply functions of the Chao-Peck 6-node example.

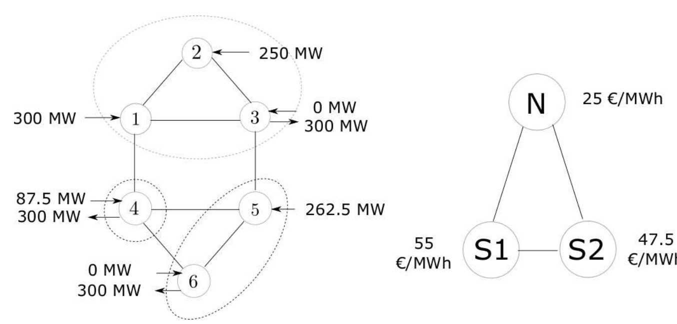

Fig. 2: Day-ahead zonal market clearing of the Chao-Peck 6-node example.

The zonal market outcome is producing a Northern zonal price of 25 €/MWh, a price of 55 €/MWh for Southern zone 1, and a price of 47.5 €/MWh for Southern zone 2. Both

[1]The data for the example can be retrieved at the following link: https://perso.uclouvain.be/anthony.papavasiliou/public_html/ChaoPeckDA.zip.

[2]Note that, if we were to select the minimum of any inter-zonal link between adjacent zones, we would have to choose 300 MW for link N-S1, 200 MW for link N-S2, and 125 MW for link S1-S2. Interestingly, this choice of capacity values results in congestion, when the physical flows implied by the zonal day-ahead solution are computed. Therefore, we derate these capacities even further (to one half of the above capacities), until we arrive at a physically implementable day-ahead zonal solution.

ATC links from North to South are congested. The day-ahead market clearing outcome is presented in Fig. 2. The day-ahead positions imply a certain physical flow, which we compute by using the DC (linearized) power flow equations.

B. Zonal Balancing

Suppose that an imbalance of -40 MW occurs in the Northern zone (the convention is that negative imbalance implies additional demand which appears in real time). The zonal solution that would be computed by MARI responds to this imbalance by activating +40 MW of production from location 2, which results in a physical overloading of line L23 (which would be compensated, in practice, by redispatch). The solution is shown in Fig. 3.

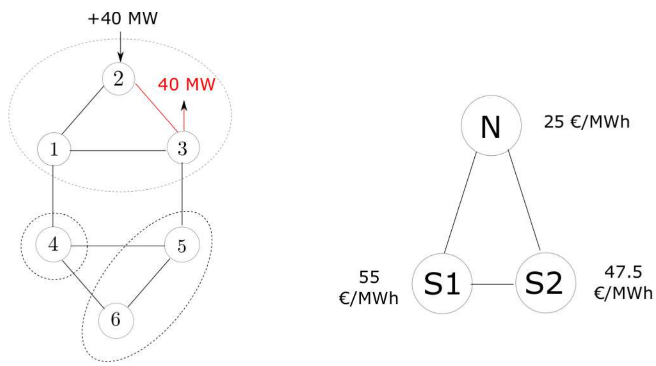

Fig. 3: Real-time zonal market clearing after an imbalance of -40 MW occurs in node 3. The flow limit of line 2-3 is violated.

C. Nodal Balancing

Consider a nodal balancing model, which relies on the line limits and PTDF matrix of Table I. The welfare maximizing nodal balancing solution is presented in Fig. 4. Note that the flow on line L23 is 170 MW, which is exactly the flow limit of the line.

To conclude, we demonstrate that balancing with a zonal model such as the one used in MARI may lead to congestion in the Northern zone if the balancing model relies on a zonal network representation. In the following section, we propose a hierarchical approach that aims to overcome this problem.

III. Hierarchical Balancing

A. Residual Supply Function

In order to overcome the overloading of transmission elements that is caused in a zonal balancing model, we propose a hierarchical approach that has also been implemented in the context of TSO-DSO coordination [12] (where it is referred to as the "Decentralized Common TSO-DSO Market"). The idea is to design a residual supply function, which is submitted to the MARI platform, instead of submitting the BSP bids individually.

Suppose that the dispatch of other TSOs does not change from the most recently metered value. We can then fix their net injections, and pose the question of what is the cheapest way (i.e. the total cost $TC(e)$ below) in which we can export a

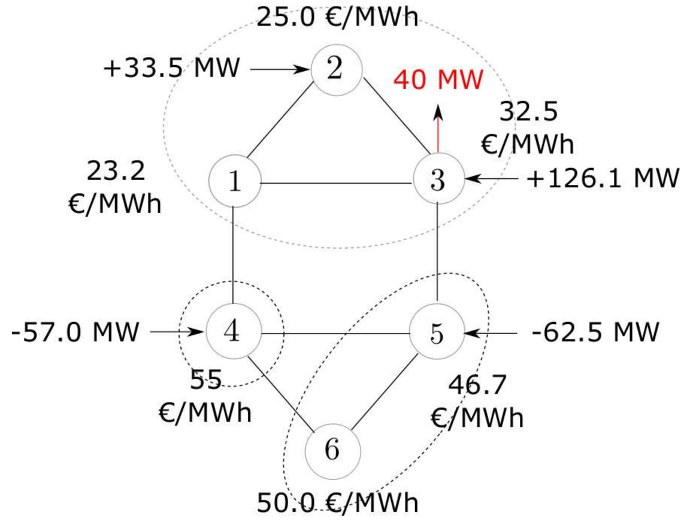

Fig. 4: Real-time zonal market clearing after an imbalance of -40 MW occurs in node 3. Transmission constraints are respected.

given amount of power (e in the mathematical model below) from the Northern zone. In terms of a generic DC optimal power flow problem, the formulation reads as follows:

$$TC(e) = \min_{p,d,r,f} \sum_{g \in G} MC_g \cdot p_g - \sum_{l \in L} MB_l \cdot d_l$$
$$r_n = \sum_{g \in G_n} p_g - \sum_{l \in L_n} d_l, n \in N_{North}$$

$$f_k = F_k^{South} + \sum_{n \in N} PTDF_{k,n} \cdot r_n, k \in K_{North}$$
$$-FMax_k \leq f_k \leq FMax_k, k \in K_{North}$$
$$(\pi) : \sum_{n \in N_{North}} r_n = E^0 + e$$
$$p_g \leq PMax_g$$
$$p_g = P_g^0, g \in G^{Slow}, d_l = D_l^0, l \in L^{Slow}$$

The notation here is as follows. Lower case corresponds to decision variables, upper case corresponds to parameters. The function $TC(e)$ is the total cost of shipping an excess supply of e MW of power from a zone to the hub node (which can be negative if the zone is importing). The set of loads is denoted as L, the set of generators is denoted as G, the set of lines is denoted as K, and the set of nodes is denoted as N. Resources that are located in node n are represented with a subscript, so for example G_n is the set of generators located in node n. We denote by K_{North} the set of lines that are located in the Northern zone (including the inter-zonal links) and by N_{North} the set of nodes that are located in the Northern zone. We have F_k^{South} corresponding to the flows that are induced in the Northern control area by resources that are not under the

TABLE I: Network data of the Chao-Peck instance used in this paper.

Line	Limit (MW)	Susceptance	PTDF 1	2	3	4	5	6
1-2	125	1	0.088	-0.530	-0.105	0.030	-0.020	0
1-3	180	1.5	0.279	-0.011	-0.332	0.094	-0.064	0
1-4	300	1.6	0.634	0.540	0.437	-0.124	0.084	0
2-3	170	0.9	0.088	0.470	-0.105	0.030	-0.020	0
3-5	200	1.1	0.366	0.460	0.563	0.124	-0.084	0
4-5	125	1.3	0.160	0.095	0.023	0.329	-0.223	0
4-6	125	0.95	0.474	0.446	0.414	0.547	0.307	0
5-6	270	1.4	0.526	0.554	0.586	0.453	0.693	0

control of the Northern TSO[3].

The net injection in node n is denoted as r_n. The flow along a line k is denoted as f_k. The production of generator g is denoted as p_g, and the demand of consumer l is denoted as d_l. Consumers have a marginal benefit of MB_l and generators have a marginal cost of MC_g. The power transfer distribution factor from node n to line k is denoted as $PTDF_{k,n}$. The flow limit along line k is denoted as $FMax_k$. The total export of the Northern zone is denoted as e. The set of generators and loads that cannot be moved in real time are denoted as G^{Slow} and L^{Slow} respectively. The day-ahead schedules are denoted as P_g^0 and D_l^0 for generators and loads respectively. The parameter E^0 corresponds to the day-ahead net export of the zone, therefore e is measuring incremental exports *relative* to E^0.

The objective function is the difference of generator cost and consumer benefit, which in the context of balancing can be interpreted equivalently as the cost of up-regulation minus the cost-saving of down-regulation. The first constraint defines the net exports of each node. The second constraint defines the flow of power along each line of the network as the sum of the flows implied by non-North resources, as well as flows resulting from Northern resources (where the latter are approximated by a linearization of Kirchhoff's power flow equations using power transfer distribution factors). The third constraint imposes limits on the line flows due to thermal or stability limits. The fourth constraint defines the net export of the zone (we explain the meaning of the multiplier π in the next paragraph). The last set of constraints fixes the set-points of resources that are not flexible to their day-ahead (or intraday) nominations. It is a simple result of convex analysis to note that $TC(e)$, is a convex function of e because the economic dispatch problem is convex. The slope of the function is the dual multiplier of the last constraint, and we denote it as π.

B. Timeline

We now outline in detail the sequence of events of the proposed hierarchical balancing approach. The sequence is depicted at a high level in Fig. 5.

1) Forecast externally imposed flows (before MARI): The idea of step 1 is to "filter out" the impact of the resources that cannot be controlled by the Northern TSO. Essentially, this

[3]Ideally, this parameter should also account for the impact of the MARI activation of Southern resources on the Northern network. This is not realistic, however, because the moment in time in which the residual function is computed is before MARI clears. Therefore, there is some inherent uncertainty regarding the actual value of this parameter.

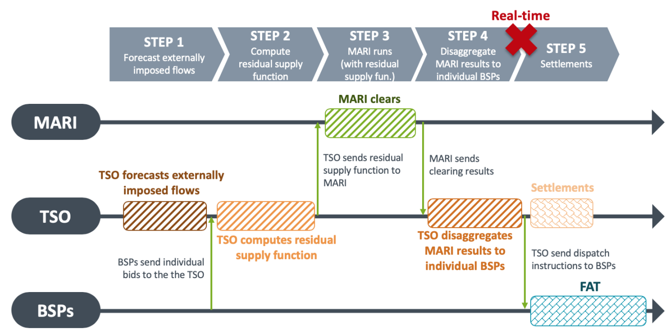

Fig. 5: Timeline of the proposed hierarchical balancing approach.

implies assigning values to F_k^{South} in the formulation above, which is a straightforward calculation for the Northern TSO based on its locally observable information: the Northern TSO subtracts from the measured flows on its lines the impact of the dispatch of the Northern resources in the previous imbalance interval. Thus, no communication is required between the Northern TSO and non-Northern TSOs in order for this step to be executed.

The TSO forecasts the following flows on its network from resources that are dispatched out of its jurisdiction. For the sake of this illustration, we assume that the telemetered dispatch (or the flows estimated by the state estimator) is the one that corresponds to the day-ahead zonal market clearing (Fig. 2), and not the infeasible MARI activation (Fig. 3). (i) Line 1-2: -11.6 MW; (ii) Line 1-3: -36.8 MW (iii) Line 1-4 (inter-zonal): 48.4 MW; (iv) Line 2-3: -11.6 MW; (v) Line 3-5 (inter-zonal): -48.4 MW.

2) Compute residual supply function for MARI: In this stage, the Northern TSO estimates the residual supply function that it plans to submit to MARI. The estimation of the residual supply function requires the resolution of as many OPFs[4] as the points around which we wish to approximate the residual supply function. In our example, we approximate the residual supply function around 10 points, which are centered around the day-ahead net export quantity. The resulting residual supply function is presented in Fig. 6. The horizontal axis in the residual supply function corresponds to the change in export, relative to the day-ahead schedule.

[4]The residual supply function is obtained as the subgradient of the function TC with respect to e, which is computed when solving the linear program expressed above.

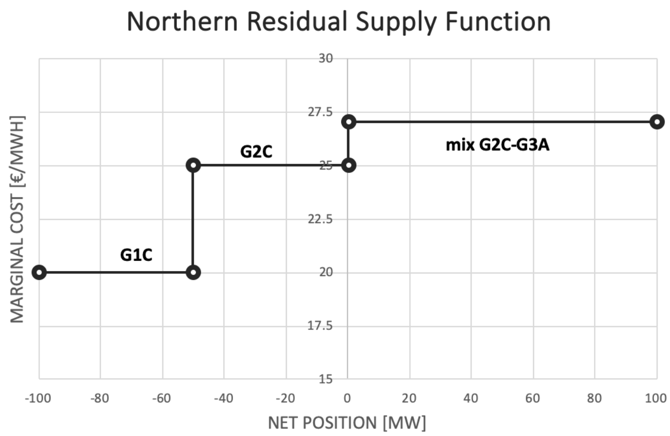

Fig. 6: Residual supply function in step 2 of the hierarchical balancing method.

3) Clear MARI with Northern residual supply function: In this stage, the residual supply function that is computed in step 2 is converted into synthetic BSP bids (i.e. the function is discretized, each piece being considered as a bid for MARI) and inserted in the MARI market clearing platform. The idea is that the North zone will export its scheduled volume, and any imbalances will be dealt with via a delta on the net position (relative to a day-ahead or intraday schedule), the marginal cost of which is computed from the residual supply function of the previous step.

In terms of the example, the MARI platform clears with the residual supply function of the previous step. The activated supply from the Northern aggregate supply function is +40 MW. The Northern clearing price amounts to 27.05 €/MWh, which corresponds to the marginal cost function that is plotted in figure 6. The resulting clearing quantities and prices are presented in figure 7. It is interesting to note that the North price is now higher (27.05 €/MWh) than with the straightforward zonal clearing before (25 €/MWh), because the constraints in the Northern zone are already accounted for.

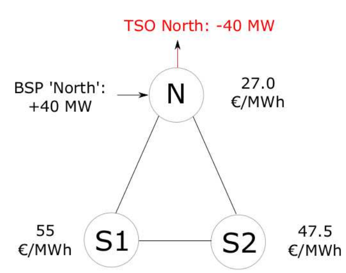

Fig. 7: Zonal market clearing in step 3 of the hierarchical balancing method.

4) Disaggregate the results of MARI in the Northern zone: In this step, the Northern TSO needs to allocate the activation decided by MARI to the BSPs within its zone. The idea is for the Northern TSO to run an optimal power flow limited to its own zone. This implies that the dispatch actions of the Northern TSO may cause problems outside of the Northern zone. If the entire Northern zone is bid as a single "BSP" by the Northern TSO, then there is nothing inconsistent with the actions of the Northern TSO. The platform instructions are followed, and there is no net payment due to the platform.

In terms of the illustrative example, given an instruction of +40 MW upward activation by the MARI platform, and given the observed imbalances within the Northern zone, the Northern TSO can solve an OPF in order to clear its imbalances and deliver its promised net injection to the platform. The assumption here is that the forecast of the Northern TSO about the effect of non-North resources on the flows of Northern lines is accurate (whereas, in reality, the actual physical flow may deviate). The actual dispatch of the system is presented in figure 8. The dispatch within the Northern zone turns out to be identical to that of the nodal proxy approach of figure 4. Note that each node of the Northern grid has an associated nodal price.

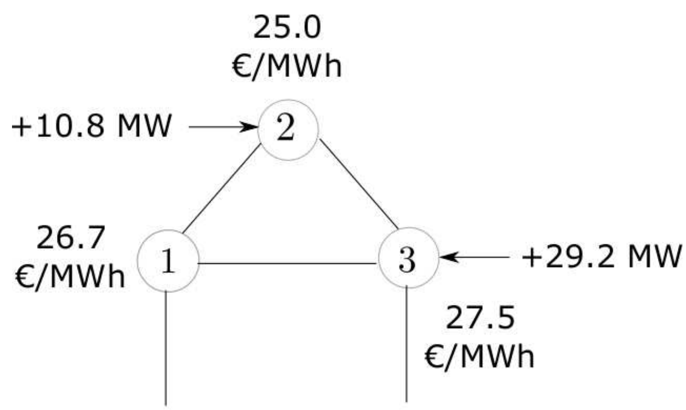

Fig. 8: Disaggregation in step 4 of the hierarchical balancing method.

5) Settlements: The Northern TSO implements a nodal system within its own zone when disaggregating resources. The Northern TSO thus collects a payment as an aggregate BSP (step 3, MARI), and then uses these funds to procure balancing power in the disaggregation phase (step 4). Table II presents the settlements.

IV. Implementation

The following discussion on legal aspects is based on the examination of European Commission regulation 2017/2195 (the electricity balancing guideline / EBGL) [8], and how it interacts with our proposal. There are consistent statements in the EBGL which raise encouraging signals but also potential challenges.

a) Merit order: The fact that the hierarchical balancing approach produces a merit order list for MARI is consistent with EBGL requirements on submitting merit order lists in order to ensure cost-efficient activation of bids. Relevant articles are 0(11), 21(3k).

b) Compatibility with TSO-TSO model: The definition of a TSO-TSO model is one in which the BSPs interact with non-domestic TSOs through their domestic TSO (as opposed to directly). This seems compatible with what is being proposed

TABLE II: Settlements in the proposed hierarchical balancing approach.

	Day-ahead	Step 3 (MARI)	Step 4 (post-MARI)	Total	Total MARI + post-MARI
G1 (BSP)	7500	0	0	7500	0
G2 (BSP)	6250	0	270	6520	270
G3 (BSP)	0	0	803	803	803
BSP "North"	0	1080	0	1080	1080
L3 (BRP)	-7500	-1080	0	-8580	-1080
South BSP	17281	0	0	17281	0
South BRP	-30750	0	0	-30750	0
North TSO	3375	0	-1073	2302	-1073
South TSO	3844	0	0	3844	0
Total	0	0	0	0	0

in the hierarchical balancing approach. Relevant article is 2(21).

c) Forwarding BSP bids to the platform: There are certain provisions in EBGL which suggest that the TSO is required to forward its domestic bids directly to the platform. These provisions may be at odds with the aggregation that is being proposed in the pre-MARI step of the hierarchical balancing approach. Relevant articles are 2(38), 12(b), 16(2), 21(6a), 29(9), 33(3). Limitations on this practice are foreseen, subject to regulatory approval, in article 5(4e).

d) Integrated scheduling process in central dispatching: There are explicit provisions in the EBGL regarding the conversion of bids, by TSOs operating an integrated scheduling process within a central dispatching context. The conversion of bids from an integrated scheduling process is discussed explicitly in articles 12(3c), 12(3d), 18(8d), 27(3). TSOs that wish to apply a central dispatching model need to notify the relevant regulatory authority, as foreseen in article 14(2). One concern about this interpretation is that the spirit of these provisions is to allow the mapping of bids submitted in a unit commitment tool to bids that are submitted to an exchange. Concretely, the integrated scheduling process receives information about startup cost, min up/down times, ramp rates, technical minima, min load cost, etc., whereas the balancing platforms will require much simpler bids which internalize many of these factors. Therefore, the interpretation of the integrated scheduling process articles as a means of avoiding congestion could be challenged.

V. Conclusion

We present a hierarchical balancing model which aims at being compatible with the bidding format of MARI while respecting the physical constraints of the network. The approach manages to represent implicitly the internal grid constraints of the TSO within MARI, while leaving the design of MARI untouched. This improves economical efficiency, while keeping the implementation challenges manageable. We demonstrate the approach on a simple example, and discuss implementation challenges.

An important observation is that the residual supply function is one-dimensional as long as we are focusing on a single dispatch interval. The approach would need to be generalized in a more realistic setting where a single TSO manages multiple zones. On the other hand, the fact that there may be multiple zones to which the Northern zone is connected does not mean that the total cost function is multi-dimensional. This may not be true if the inter-zonal connectors are HVDC lines (which imply a controllable flow[5]), or if we are considering total cost over multiple periods.

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[5]This means that we would be considering the residual supply function in the dimension of (i) the total uncontrollable flows through AC links, and (ii) one dimension per controllable link / HVDC.