A Greedy Approach and its Limitations for Day-ahead Co-allocation of Energy and Reserves

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***Abstract*— In this paper we consider a multi-zonal day-ahead market clearing setting, in which energy and reserves are simultaneously allocated. We present an iterative heuristic approach for the joint procurement process, which is based on the greedy algorithm. We demonstrate via an example that this simple approach cannot be expected to reach global optimum in general and discuss its further improvement possibilities.**

***Index Terms*-- Day-ahead electricity markets, Joint energy-reserve markets, Cross-border reserve trading**

I. Introduction

While market coupling of day-ahead energy markets is already established in the EU [1], frequency restoration reserves are usually still allocated exclusively inside control zones and typically no inter-zonal procurement is realized. Although it is clear that the coordination of reserve sizing, procurement and activation processes would significantly improve the efficiency of these markets, and it has been pointed out that efficient balancing markets are a prerequisite for the integration of renewable sources [2], the integration of reserve markets proves to be a more challenging area. One underlying reason for this is that if reserves are allocated with zonal imbalances, or coordinated activation of reserves takes place, the flows arising in the case of activation require available transmission capacity. In this case this transmission capacity must be pre-allocated for the possible activation, which potentially limits the volume of inter-zonal day-ahead energy trading. To achieve a social optimum in the context of multiple markets, energy and reserve products must be co-allocated in a coordinated manner, considering transmission constraints as well. In this context, one may consider the network transmission capacities as goods which have to be allocated either for energy or reserve trading (up to a certain degree in both cases), but the problem is further complicated by the fact that since trading between two zones implies flows on all possible paths in the network between the two zones, strong complementarities arise between various capacity products.

A. Related Literature

The basic elements of design principles for cross-border balancing electricity markets are summarized in [3]. The recent studies [4], [5] analyze the benefits implied by cross-border reserve trading and coordination in a unit-commitment framework. The paper [6] also uses a unit-commitment approach to estimate the benefits of coordinating sizing, allocation, and activation of reserves among market zones. In the current paper we do not analyze the benefits implied by coordinated activation of reserve resources or by coordinated sizing, but we focus solely on the procurement process, considering the benefits implied by coordinated procurement in a day-ahead market aspect, measured by the welfare resulting from the market clearing process.

B. Contribution

Our aim in this paper is to study the problem and a potential solution approach on a simplified one-period day-ahead market setting, in which we omit non-convex bids (i.e., partial acceptance is allowed for all bids). In the proposed market clearing model we consider the joint (energy-reserve) market coupling of multiple zones, as pairwise transactions of various products between certain zone pairs. Furthermore, for the aim of simplicity, in this study we only consider a single type of reserve, namely upward manual frequency restoration reserve

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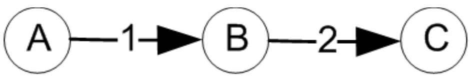
(upward mFRR) – however the proposed principle may be easily generalized for simultaneous allocation of up and down reserves. To demonstrate the greedy approach in the context of energy-reserve co-allocation, and its limitations, we introduce a simple example.

II. Model

A. Network

We consider a simple 3 zone-network depicted in Fig. 1, where all line capacity limits are assumed to be equal to 1 unit.



Simple example network. The direction of the edges correspond to the reference direction of positive flows.

B. Day-ahead market model

We consider the most simple day-ahead market model, where simple step-wise quantity-price type bids are submitted on both the supply and demand side. We assume the energy (E) and up reserve (U) bids summarized in Table I. Negative quantities correspond to supply bids.

TABLE I. Energy and Reserve Bids

Bid ID	product type	quantity	price (per unit)	zone of submission
E1	E	-2	6	A
E2	E	-1	11	A
E3	E	-1	7	B
E4	E	-1	11	B
E5	E	-1	8	C
E6	E	-1	11	C
E7	E	1	8	A
E8	E	1	4	A
E9	E	2	8	B
E10	E	2	10	C
U1	U	-2	4	A
U2	U	-1	8	A
U3	U	-2	4	B
U4	U	-1	8	B
U5	U	-1	6	C
U6	U	-2	8	C
U7	U	1	5	A
U8	U	1	2	A
U9	U	1	5	B
U10	U	1	2	B
U11	U	2	7	C

The aggregated bid curves of each zone are depicted in Fig. 2., where the intersection points determine the resulting market clearing prices (MCPs) in the case of fully decoupled markets: [6 8 10] for E and [4 4 7] for U for the zones A, B and C respectively. Looking at Fig. 2, based on the areas between the aggregate demand and supply curves, it is easy to determine the resulting total social welfare (TSW), which is equal to 8 units in the case of fully decoupled markets.

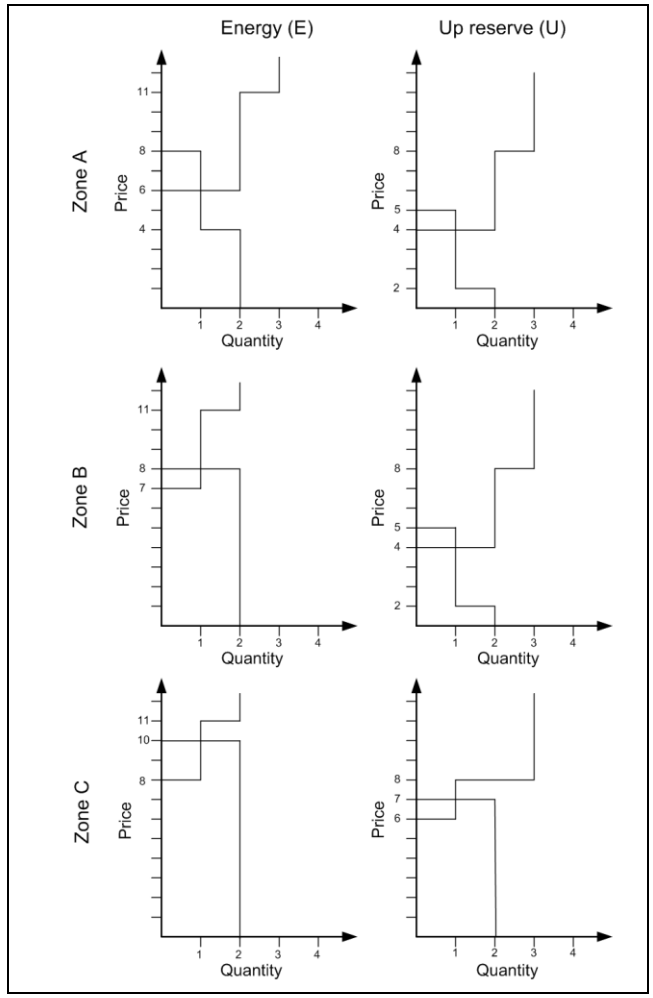


Figure 1. Aggregated bid curves of E and U bids in the zones A, B and C.

C. Joint Iterative Procurement Model

The joint procurement model of energy and reserves based on the greedy approach considers the fully decoupled case as reference and iteratively allows individual transfers of certain product types between zone pairs, taking into account the benefit implied by the transfer, and the necessary capacity allocation aspects. More precisely, the marginal benefit of the transfer is considered, which may be regarded as the benefit implied by the transfer of one unit of the product, assuming every bid quantity (and line capacity) is an integer value (as in our case). Based on the bid parameters summarized in Table I, and on the implied aggregated supply-demand curves depicted in Fig. 2, one determined the benefits of the potential transfers. Considering e.g. 1 unit of E transfer from zone A to zone B means, that the two markets are cleared, assuming a supply-demand balance (i.e. net position) of 1 units in A, and -1 units in B. In this particular case this will imply a total supply and demand of 2 and 1 units respectively in zone A, and a total supply and demand of 1 and 2 units respectively in zone B. The original market clearing prices (MCPs) will be still valid in this case, implying a TSW equal to 10, thus a TSW increment of 2 units (since 1 unit of energy produced in A at the price of 6 is transferred to B, where it is sold at the price of 8). In this case, the implied transfer of 1 unit on line 1, fully exploiting its capacity. In general, modifying the supply-demand balance constraints of the market clearing problem, and solving it for the zone-pair in question, optimizing the total TSW of the two markets determines the marginal contribution of the transfer.

One step of the proposed algorithm is as follows. Considering the actual state of the markets and the network (which is determined by full decoupled clearing in the first step), the algorithm considers each product types (in this case E and U) and each possible zone pair. For every such possibility, the marginal TSW contribution and line-load feasibility is evaluated. If there are no feasible transfers, which increase the resulting total TSW the algorithm stops. If there is at least one feasible transfer, which implies a TSW increase, the transfer with the highest TSW benefit is identified, and it is allowed up to the amount, which is (1) still feasible in the context of line loads and (2) is invariant regarding the marginal TSW contribution. Let us note that the quantity up to which the marginal TSW contribution is invariant is easy to determine in the case of standard bids allowing partial acceptance, based on the evaluation of the aggregated supply and demand curves, but is more non-trivial in the case, when non-convex bids are also present. Following this step, the market and flow states are updated. Market states are described by MCPs and acceptance indicators, while flow state correspond to the worst-case flows of lines. The worst-case flows have deterministic components, implied by inter-zonal energy transfers, and stochastic components, implied by the inter-zonal activation of reserves. In the current framework, for the aim of simplicity, we assume an 'own first' activation of reserves. This means that if e.g. 2 units of reserve demand and 1 unit of reserve supply has been allocated in zone A, and 1.5 units of reserve demand is later activated, 1 unit is covered from the locally procured reserve supply (independent of the activation price). This assumption ensures, that the worst-case line loads are 0 for all lines in the initial case, when fully decoupled clearing is present. The algorithm is summarized in Fig. 3.

It is easy to see that a subset of possible transfers may be excluded from the considered set, which do not need to be individually evaluated, since if the MCP of product P is lower in zone X compared to zone Y, the transfer of the product from X to Y will not imply any benefits.

If we apply the algorithm for the simple 3-zonal market example described earlier, we may evaluate all possible transactions, as described in Table II.

The proposed algorithm will choose the transfer of energy from zone A to zone C, up to the amount of 1 unit, which already saturates the transmission capacity of both lines, implying that no further transfers are possible, thus the algorithm stops, resulting in a total TSW of 12 units, meaning an increase of 4 units.

It is easy to see that this is however not the optimal solution. If we allow the transfer of 1 unit E from zone A to zone B and the transfer of 1 unit U from zone B to zone C, the resulting worst-case flows (1 unit on both lines) are feasible, but the TSW is increased by 5 units (2+3 regarding the E and the U transfer respectively).

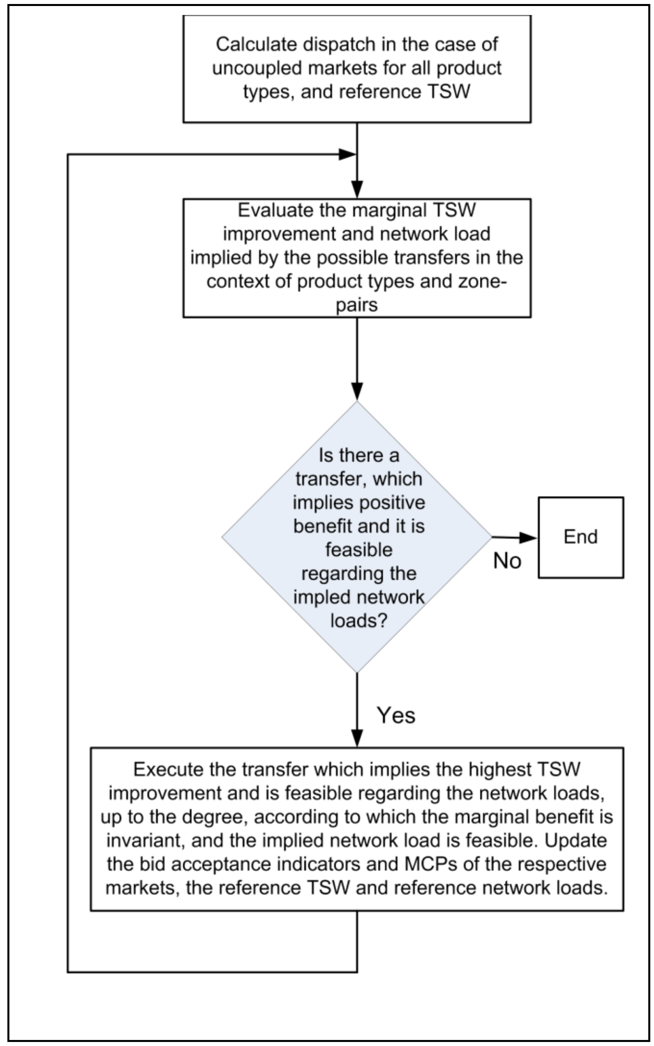


Figure 2. The greedy algorithm based scheme of the iterative co-allocation proces.

TABLE II. TSW IMPROVEMENT IMPLIED BY VARIOUS POSSIBLE TRANSFERS BETWEEN ZONES

transfer	E	U
A → B	2	0
A → C	4	3
B → C	2	3
C → B	0	0
C → A	0	0
B → A	0	0

III. DISCUSSION

A. Drawbacks and Benefits

The above simple example very clearly shows that such local search algorithms cannot be expected to reach global optimum in the case of joint procurement. However, we argue that potential heuristically modified future versions may be still worth to investigate. Let us point out some benefits of the approach, compared to other possible, more complex integrated clearing algorithms.

- The computational burden of a single step of the algorithm is relatively low, as in every case, only the market-coupling of two zones must be evaluated. If high number of zones is present, each including a high number of bids – which is realistic, especially in the case of multiple products considered –, the simultaneous clearing of all of the included markets may be computationally challenging, even under the assumptions of predefined capacity allocation constraints (e.g. if the 10% of transmission capacity may be used for cross-border reserve trading). One may however argue that the number of zone-pairs, for which the market-coupling based evaluation must be carried out grows exponentially with the number of zones.
- Let us emphasize however, that the proposed algorithm may be well implemented in a parallelized framework. The evaluation of each case summarized in Table II may be done independently.
- Finally, for such a complex problem like the multi-zonal joint procurement of energy and reserves, it may be useful to have sub-optimal algorithms for backup, which may still induce significant TSW improvements in the procurement process.

B. Application in the Case of More Complex Network Topology

In this paper we presented an example using the simplest topology, which is able to demonstrate the phenomena of suboptimality. If the number of zones and lines is higher, thus the topology is more complex, the network loads implied by the individual transfers of the iteration process may be calculated using the power transfer distribution factors (PTDF) [7], and the reference network load is updated accordingly, resulting in an iterative allocation of available transmission capacity.

C. Potential Improved Versions

A potential simple improved version of the algorithm corresponds to the modification, according to which we do not evaluate the TSW benefit implied by a certain transfer, but the *normalized* TSW benefit, which is the TSW increase, divided by the total increase in the implied (worst-case) line flows. In the case of the proposed 3-zone example, even this very simple improvement is enough to identify first the B → C U, then the A → B E transfers, and thus to avoid suboptimality. However, in general, it is clear that this approach will not guarantee global optimality either.

The normalization of the TSW increase however may be further improved, based on more sophisticated intuitions. If one has either prior information of potential network bottlenecks, or this measure is calculated and updated in each step of the algorithm, one may use a normalization, which implies higher penalty for transfers resulting in larger flows on these bottleneck lines. For example, a weighted average is possible, where the weights corresponding to individual lines are determined by the reciprocal of the remaining free transmission capacity of the corresponding line in the direction of the load. Several directions of such heuristics are possible, and they must be subject to further studies on the subject.

As it has been discussed earlier, the proposed approach may be easily generalized if not only up but also down reserves are taken into account, however this is not necessarily true, if multiple types of a single reserve are considered, which are partially substitutes for each other – in such a case, the generalization of the algorithm is non-trivial, and needs further considerations.

IV. CONCLUSIONS AND FUTURE WORK

In this simple study we have shown that the coordinated multi-zonal procurement of energy and reserves may be considered in the context of transfers between zone-pairs, which are evaluated according to the implied TSW benefit and network load. Starting from the totally uncoupled case, which is considered as reference, it is possible to use a greedy algorithm to iteratively allow the most beneficial pairwise transfers of either energy or reserves and update the potential network loads accordingly. As we have shown in the case of a simple example, this approach cannot be expected to reach the global optimum in general. However, the approach has such properties, which may be beneficial in the case of large-scale implementation (parallelizability), and further heuristics may lead to market clearing solutions, which are in general potentially still suboptimal, but on the one hand they may allow significant gain compared to approaches, where the transmission capacity of lines is allocated in prior between energy and reserve trading (e.g. is the policy maker states prior that 90% of line capacity may be used for energy transfer and 10% for reserve transfer), and may be calculated in a computationally efficient way. Future studies based on realistic bid and network data are required to determine the efficiency of the proposed approach and its improved future versions.

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