21, rue d'Artois, F-75008 PARIS
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Optimal Activation of Standard Products for Balancing as Required by Draft ENTSO-E Network Codes

M. HÅBERG, G. DOORMAN
Statnett, Norwegian University of Science and Technology
Norway

SUMMARY

As a part of the new cross-border balancing arrangements in Europe, the Network Code on Electricity Balancing, developed by ENTSO-E, requires Standard Products for Operating Reserves to be defined for the exchange of balancing energy between market areas. Activation of balancing bids will be coordinated by an Activation Optimization Function. To ensure efficient use of balancing resources, the activation algorithm must select between bids with different prices and locations, but also choose between the different products, which may have different activation time and minimum duration. This algorithm is yet to be designed.

This paper investigates how Standard Products can be activated to cover an imbalance forecast at minimum cost as a scheduling problem using mixed integer-linear programming. Case studies also investigate the impact on costs of using only a single Standard Product, imposing a merit order restriction or planning only 15 minutes ahead.

The analyses show that the optimal activation not necessarily follows the merit order, but for the cases studied, imposing a merit order activation for bids of the same product was found to have low impact on costs. Using more than one Standard Product can likely reduce imbalances and the necessary amount of aFRR capacity. Disregarding information on future imbalances reduces computational complexity, but provides costly and unattractive activation schedules.

KEYWORDS

activation optimization function, balancing market integration, cross-border balancing, frequency restoration reserves, imbalance forecasts, standard products

martin.haberg@ntnu.no

1 INTRODUCTION

1.1 Integration of European Balancing Markets

For many years, the European Union has pursued the vision of establishing an integrated electricity market in Europe, including balancing markets. An important motivation has been to increase efficiency in utilization of balancing resources [1], but also reducing the high concentration in many markets [2].

Balancing markets can be seen as the liberalized, market-based approach to balance management, "consisting of three main pillars: balance responsibility, balance service provision, and imbalance settlement" [3]. For the European balancing markets to be integrated, national and regional differences have to be overcome [4] in all of these pillars, i.e., harmonization is necessary. The Network Codes currently being developed by the European Network of Transmission System Operators (ENTSO-E) establish common market rules and regulations, and the Network Code on Electricity Balancing [5] aims to facilitate cross-border exchange of balancing services and integration of balancing markets.

1.2 Reserves, Standard Products and Activation Markets

ENTSO-E categorizes reserves into Frequency Containment Reserves (FCR), Frequency Restoration Reserves (FRR) and Replacement Reserves (RR) [6]. Automatic (aFRR) and manual FRR (mFRR) are similar to secondary and tertiary reserves, respectively. The FRR products used differ widely between European TSOs. For cross-border exchange of these products, ENTSO-E has decided upon a Common Merit Order List (CMOL) approach [5]. In order to facilitate cross-border balancing, ENTSO-E is currently developing *Standard Products* for balancing energy. The Standard Products will define the technical requirements on bids submitted for FRR and RR. Among the characteristics are the activation time and min and max duration of the products.

An *Activation Optimization Function* will operate an activation market, performing a joint optimization of the balancing energy requests from TSOs in the CoBA using bids from the CMOLs. Neither [5], nor [7] provide details on the algorithm principles. Traditional balancing activation markets have often been single buyer auctions, with the TSO purchasing sufficient balancing energy to cover the imbalance through a marginal loading procedure. More sophisticated approaches, such as proactive balancing [8] are less intuitive, but may give lower activation costs.

1.3 Focus and Outline of Paper

The balancing energy activation problem resembles an economic dispatch, but finding the optimal activation decision is complicated when selecting between bids which not only have different prices, sizes and locations, but also are subject to temporal constraints. They also belong to distinct products with differing time constants. Under these conditions, merit order activation does not guarantee optimality.

This paper investigates how Standard Products for mFRR can be activated in a cost-optimal way using imbalance forecasts and a cost minimizing algorithm. Network congestion has been left outside the scope of the model. The optimization approach is described in Section 2, followed by results in Section 3 indicating how strict merit order activation and short-term-only scheduling increase costs. The added value of having more than one mFRR product is also investigated. This is discussed in Section 4, leading to the conclusions in Section 5.

2 INTRODUCTION

2.1 Model Formulation

The formulation proposed here is a scheduling problem, assuming credible information on the future imbalance (cf. Figure 1). The optimal activation decisions will give an activation schedule that minimizes the objective function while satisfying all constraints. The constraints, most of which are related to the technical characteristics of the system, evaluate the feasibility of a solution, while the objective function evaluate the performance of the solution in terms of costs and frequency deviations.

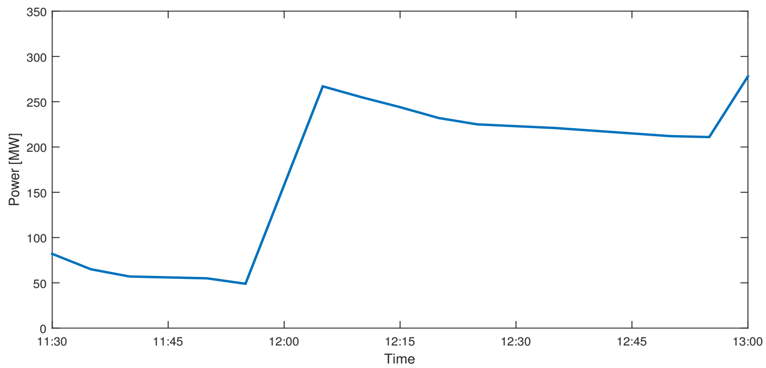

Figure 1 Imbalance forecast for afternoon, 4 Feb 2014

The model is formulated using a MILP structure with 5-minute time steps and is implemented in Xpress[1]. It minimizes the sum of the cost C^a of activated energy and a penalty cost C^p , cf. (1)-(3). The activation cost is given by bid costs c_b for each bid b in the upward and downward direction, and corresponding activation amounts y_b for each time step t. p^{DA} is the clearing price in the day-ahead market. Penalty costs used for ensuring frequency restoration and are calculated as a piecewise linear function of the estimated frequency deviation.

$$\min C = C^a + C^p \tag{1}$$

$$C^a = \sum_{t\in T}\left(\sum_{b\in B_u} c_b y_{b,t} + \sum_{b\in B_d}(p^{DA} - c_b)y_{b,t}\right) \tag{2}$$

$$C^p = \sum_{t\in T}\sum_{k\in K} p_k\left(f_t^{ok} + f_t^{uk}\right) \tag{3}$$

For the discrete time steps used in the model, the frequency f_t at a given time t is estimated using the frequency bias λ together with the imbalance forecast ω_t and the activated power $y_{b,t}$ delivered from each of the bids, as shown in (4).

$$f_t = f_N + \frac{1}{\lambda}\sum_{t\in T}\left(\sum_{b\in B_u} y_{b,t} - \sum_{b\in B_d} y_{b,t} + \omega_t\right) \quad \forall\, t \tag{4}$$

Minimum and maximum capacity constraints are defined similarly to [9], using generation variables $y_{b,t}$ and a single set of commitment variables $u_{b,t}$. In addition, binary variables $v_{b,t}$ govern the ramping restrictions in (5)-(8). Note that this is a block formulation, i.e. the energy during ramping is not taken into account in the optimization.

$$y_{b,t} \le \overline{y}_b u_{b,t} \qquad \forall b, \forall t \tag{5}$$

$$y_{b,t} \ge \underline{y}_b u_{b,t} \qquad \forall b, \forall t \tag{6}$$

$$y_{b,t} \le y_{b,t-1} + \overline{y}_b x_{b,t} \quad \forall b, \forall t \tag{7}$$

$$y_{b,t} \ge y_{b,t-1} - \overline{y}_b x_{b,t} \quad \forall b, t > 1 \tag{8}$$

The Zendehdel linearization [10] is used for minimum duration constraints. Initially activated bids are forced in (9) to stay in operation for their minimum remaining duration L_b. Eq. (10) requires bids started up at s to fulfil their minimum duration. Bids activated close to the horizon $|T|$ may be forced by (11) to remain activated throughout the horizon.

[1] FICO® Xpress optimization suite v7.8, 2015

$$\sum_{t=1}^{L_b} u_{b,t} = L_b \quad \forall b \tag{9}$$

$$\sum_{t=s}^{s+\underline{DP}_p-1} u_{b,t} \geq \underline{DP}_p\left(u_{b,s} - u_{b,s-1}\right) \quad \forall b, s \in \left\{1 + L_b + 1, \dots, |T| - \underline{DP}_p + 1\right\} \tag{10}$$

$$\sum_{t=s}^{|T|} u_{b,t} \geq \sum_{t=s}^{|T|}\left(u_{b,s} - u_{b,s-1}\right) \quad \forall b, s \in \left\{|T| - \underline{DP}_p + 2, \dots, |T|\right\} \tag{11}$$

The maximum duration constraints have not been considered in this formulation. Straightforward constraints regarding initialization and start-up behavior have been omitted here.

2.2 Data Inputs and Model Parameters

A series of imbalance forecast values for Norway, Feb 4 2014 was used (cf. Figure 1). This forecast was found as the difference between a day-ahead load forecast and scheduled values for power generation and exchange. A balancing activation market consisting of 50 bids was modelled based on information from prices and volumes in the Nordic Regulating Power Market. All bids have an associated price, capacity and product type. The Standard Products are based on an early proposal from ENTSO-E, and their most important characteristics are reproduced in Table 1. The frequency bias λ has been set to 7000 MW/Hz, similar to the Nordic system [11]. The Nordic system does not presently apply automatic reserves, and aFRR activation has been disregarded in the optimization. It could in principle be included as a flexible and expensive resource of last resort, without changing the main principles of the Standard Product optimization.

PRODUCT	FULL ACTIVATION TIME	MINIMUM DURATION	DEACTIVATION TIME
P1	15 min	15 min	15 min
P2	10 min	10 min	10 min
P3	5 min	5 min	5 min

Table 1 Standard Product Characteristics

2.3 Scenarios

The four scenarios listed in Table 2 were used to analyze alternative activation arrangements. The reference scenario uses the model formulation given by (1)-(11). For the single product scenario, all bids are assumed to have P1 characteristics. In the Merit order scenario, the model imposes an additional constraint requiring every bid to be activated to its full capacity before a more expensive bid for the same product and direction can be activated. In the short run scenario, scheduling is done in six steps, looking only 15 minutes ahead. Schedules are coupled through initialization of commitment variables and information on past events.

SCENARIO	HORIZON	PRODUCTS	SELECTION
REFERENCE	90 min	P1, P2, P3	Cost minimization
SINGLE PRODUCT	90 min	P1	Cost minimization
MERIT ORDER	90 min	P1, P2, P3	Price order
SHORT HORIZON	15 min	P1, P2, P3	Cost minimization

Table 2 Scenario configurations

3 RESULTS

Figure 2 shows the estimated frequency for all scenarios during the first 30 minutes. As expected, the Single product scenario needs 15 minutes to restore frequency. After 30 minutes have passed, all schedules follow the imbalance forecast closely, keeping estimated frequency stable at 50 Hz. This is reflected in the costs in Table 3. The Single product scenario has high penalty costs due to the first 15 minutes. This is not compensated by the lower activation cost, which is related to the scenario's inability to bring the frequency back to nominal in the first 15 minutes. The short horizon scenario has the lowest penalty costs of all scenarios, but high activation costs due to poor utilization of the least expensive resources. The Merit Order scenario is almost similar to the reference in this formulation.

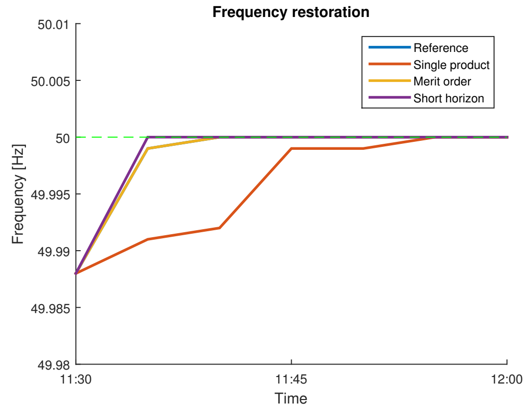

Figure 2 Estimated frequency for all scenarios

SCENARIO	ACTIVATION	PENALTY	TOTAL
REFERENCE	9 323	722	10 045
SINGLE PRODUCT	8 979	1 642	10 621
MERIT ORDER	9 324	743	10 068
SHORT HORIZON	9 552	687	10 239

Table 3 Activation costs, penalty costs and total costs

(a) Reference scenario

(b) Single product scenario

(c) Merit order scenario

(d) Short horizon scenario

Figure 3 mFRR activation by product for different scenarios

Figure 3a-d shows the delivered power from each product for each scenario. For all scenarios where available, power is delivered from P3 bids during the first part of the scheduling horizon, before being substituted and supplemented by slower products. The schedule in Figure 3b follows the 5-minute steps of the imbalance forecast closely using only a 15-minute product. This is possible by activating parallel bids at consecutive time steps. The ability to cope with unforeseen step changes is limited, and as a result, more aFRR capacity would be needed compared to the reference case.

(a) Highest upward regulation marginal price for all scenarios

(b) Lowest downward regulation marginal price for all scenarios

Figure 4 Marginal pricing maximum and minimum values

Figure 4a shows the price of the most expensive delivering bid for upward regulation among all products for each scenario, illustrating how Reference scenario makes use of more expensive bids than the Merit Order and Short Horizon scenarios large parts of the time. I.e., even though *costs* are lower, the *price* will be higher following the reference methodology. The Single Product scenario activates expensive bids to be able to follow the profile of the imbalance forecast. This is also the case for downward regulation in Figure 4b.

4 DISCUSSION

4.1 Discussion of Results

For the Reference and Merit order Scenarios (cf. Figure 3a and c) there is a tendency of cross-product equilibrium towards the end of the scheduling horizon. Here, long lead times reduce the impact of temporal constraints and their shadow costs, allowing slower products to be competitive in the product mix on the basis of lower price. Such a state of cross-product equilibrium is not evident for short horizons in Figure 3d, showing an oscillatory behavior.

Apparently, the cost increase from enforcing merit order activation is small. This is to some extent caused by the disregard of maximum duration and other temporal constraints. This allows the model to establish a base/peak load schedule, stabilizing the marginal pricing (cf. Figure 4).

4.2 Model Formulation and Implementation

The use of penalty costs in the objective function influences the search for optimal solutions. When setting the penalty levels very high, as was done in this case, the optimal solution is a minimum deviation solution. Lower penalties will create a multi-objective problem, rather than a soft constraint.

The problem formulation disregards forecast uncertainty, which may be a good approximation in the very short run. Uncertainty should be taken into account through rolling updates and re-optimizations, and in this setting, a stochastic formulation would likely perform even better in terms of costs, but at the cost of increased computational effort.

As the variables $u_{b,t}$ and $v_{b,t}$ must take integer values in a feasible solution, integer programming solution methods, such as branch-and-bound are used by the solver. The computational complexity the optimization problem is driven primarily by the amount of binary variables, and for long horizons and realistic-size CMOLs, optimality may not be proven within the desired time, but near-optimal solution can likely be found in the order of minutes. For the problem sizes used in these scenarios (1900 binary variables), the solver is usually able to close the MIP gap to less than 0.5 \% in less than a minute. Each of the 15 minute subproblems in the Short horizon scenario are solved in less than a second.

4.3 Further Work

The possibility of congestion can be taken into account by including a grid model (e.g. dc) in the optimization formulation. Current research investigates using the aFRR activation cost as an alternative to the frequency deviation penalty. This research also includes energy delivered during ramping to give more realistic activation patterns, likely reducing activation volumes and costs.

5 CONCLUSION

Balancing energy activated for frequency restoration must restore frequency at minimum cost. The characteristics of Standard Products requires using information on the future imbalance in the optimization. Using imbalance forecasts, the balancing energy scheduling approach presented in this paper finds the minimum cost schedule that also restores frequency.

Using only a single mFRR product is found to give higher estimated frequency deviations due to slower mFRR response. Short horizon scheduling is computationally efficient, but provides higher costs and increases operational complexity.

With no merit order restriction on activation within each CMOL, bid activation may deviate somewhat from the price order in the optimal solution. This is due to shadow costs arising from constraints on activation and duration time. Including the merit order restriction constrains the solution space, but for the simulated bid prices and imbalance, the impact on costs was found to be negligible in the test case, although this is not necessarily generally valid.

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