Frequency Restoration Reserves: Provision and Activation Using a Multi-Agent Demand Control System

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***Abstract*—In this work a control system for restoration reserve providers is proposed in which optimal biddings of restoration reserve capacity are made based on the predicted flexibility of the reserve resources within the portfolio of the reserve provider. It is assumed that the gate closure time for submitting reserve capacity bids is 1 hour before activation time. The reserve capacity bids need to be formed so that activation of the capacity is always feasible, irrespective of the consumption of the portfolio before an activation request. The determination of the optimal reserve capacity bids is only based on aggregated flexibility constraint information received by the individual flexible resources within the portfolio of the reserve provider. No further resource-specific information is used to determine the optimal reserve capacity bid. The activation and dispatch of the required power consumption at real time is done through a market-based multi-agent control system. A simulation example, in which the reserve capacity of a portfolio of batteries is simulated, proves the feasibility of the proposed approach and shows that a high precision of the portfolio response can be obtained.**

I. INTRODUCTION

Within the ELECTRA IRP [1], a high level functional architecture is proposed for the future power system focusing on decentralised control. In the proposed architecture the power system is divided in grid units, called *Control Cells*, that provide local balancing and voltage control. In the proposed web-of-cell based architecture, control cell operators are responsible to contribute to containing and restoring system frequency [2]. Frequency deviations result from active power imbalances between consumption/load/import and generation/export. In the proposed functional architecture, load frequency control is designed as a cascaded control from fast frequency containment to balance restoration control to slower balance steering control. The proposed architecture still applies the main principles of Load-Frequency Control [3].

The goal of Balance Restoration control (BRC) is to restore control cell balance and by doing so restoring inter-cell power flows to secure values. Based on the difference between scheduled power flow and measured/actual power flow across the cell borders, Balance Restoration reserves are activated. Restoration Reserves may be offered by loads, production units as well as storage units. Each Control Cell Operator is responsible for activating BRC reserves when an imbalance within his cell is detected. Dispatching the reserves by the Control Cell Operator is based on an ordered list taking into account economic factors, but potentially others as well such as the local status of the grid. Restoration reserve providers need to inform the Control Cell Operator of how much reserve capacity they have available and at what time. Next, after a reserve activation signal sent by the Cell Operator is received, the reserve provider needs to control its portfolio so that the required capacity is activated.

This work proposes a control system for restoration reserve providers in which optimal biddings of restoration reserve capacity are made based on the predicted flexibility of the reserve resources within the portfolio of the reserve provider. The biddings need to be formed so that activation of the capacity is always feasible. The activation of the required capacity is done through a market-based multi-agent control system. In this work, the biddings for restoration reserves are formed as required by the future bidladder platform, currently worked out by Elia, the Belgian Transmission System Operator. This platform is further described in section II. Section III describes the proposed control system and in Section IV the results of a simulation example are given. Conclusions and future work are presented in Section V.

II. THE BIDLADDER PLATFORM

The Belgian transmission system operator (TSO) Elia is developing a platform, the *bidladder* platform, where market players can bid in all available flexibility for Frequency Restoration Reserve services [4]. On the bidladder platform standardised products are offered by flexibility service providers, enabling the TSO to compare identical products and activate the most cost-efficient solution. Providers are allowed to submit bids on the bidladder platform until the Balancing Gate Closure Time, which is 1 hour before

TABLE I
MAIN CHARACTERISTICS OF BIDS OFFERED TO THE BIDLADDER PLATFORM.

Characteristic	Unit	Value
Volume offered	MW	Minimum 1.0 MW, 1 decimal resolution. Positive value means consume more or produce less, negative value means consume less or produce more.
Availability period	Time	Start time (xx:xx) and End time (xx:xx) where the minutes are multiples of quarter-hours.
Maximum Activation Time	15 min.	Integer, multiple of 15 Min.
Activation price	€/MWh	Positive or negative value with one decimal.
Locational Information	EAN	Mandatory for resources $\geq$ 25MW.

possible activation. The platform expects block-products, in which the volume offered (in MW) should have a minimum activation duration of 15 minutes. The bid should also include the maximal duration the bid can be activated during the availability period, expressed as the maximum number of 15 minutes the bidded power can be sustained. An overview of the most important bid characteristics are given in Table I. At each operational quarter-hour, the TSO constructs a merit order to determine which bids are to be activated. Activation requests are to start at the beginning of a quarter-hour. After an activation request, a bid should be able to ramp up to its full offered capacity within 15 minutes.

III. MULTI-AGENT CONTROL SYSTEM

This work describes a control system in which optimal biddings tailored for the bidladder platform are formed, and after an activation request, the necessary capacity is activated. It is assumed that the portfolio of the flexible service provider who is forming bids for the bidladder platform, consists of many flexible resources. No specific type of flexible resource is assumed: the proposed approach is valid for any resource that can provide flexibility under the form of shifting or altering electricity consumption or production.

The control system proposed follows a three-step approach, and is inspired by the work presented in [5]–[7]. The three steps are the following: (1) the portfolio constraints aggregation step, (2) bidladder bid definition step and (3) real-time control step. These three steps are repeated using a receding horizon approach: each hour a new bid is sent to the bidladder platform based on an update of the portfolio constraints, each quarter-hour a power consumption/production request is dispatched within the portfolio. Fig. 1 shows a schematic overview of the proposed three-step approach.

A. Constraint Aggregation Step

In the constraint aggregation step, the energy and power constraints (E^n_{min}, E^n_{max}, P^n_{min}, $P^n_{max} \in \mathbb{R}^T$) of each flexible resource within the portfolio of the service provider are

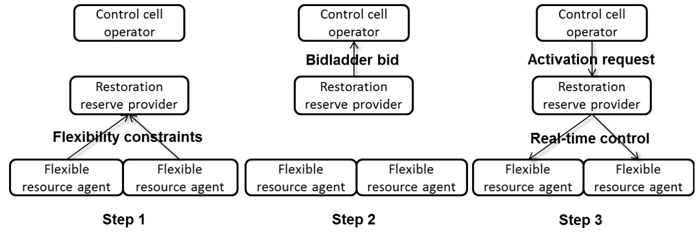

Fig. 1. Schematic overview of the three-step control system.

aggregated:

$$E_{min} = \sum_{n=1}^{N} E^n_{min} \quad (1)$$

$$E_{max} = \sum_{n=1}^{N} E^n_{max} \quad (2)$$

$$P_{min} = \sum_{n=1}^{N} P^n_{min} \quad (3)$$

$$P_{max} = \sum_{n=1}^{N} P^n_{max} \quad (4)$$

with N the total number of flexible resources. The aggregated energy constraints ($E_{min}, E_{max} \in \mathbb{R}^T$, in [MWh]) express the maximum allowed and minimally required combined energy consumption of the overall portfolio within the applied time horizon T. The power constraints (P_{min}, $P_{max} \in \mathbb{R}^T$, in [MW]) give the maximum and minimum power the portfolio can consume/produce at each instant in t during time T. The combination of energy and power constraints are an expression of the flexibility-boundaries of the portfolio. In [5] it shows how the energy and power constraints are determined by the flexible resource agents and how they are sent upwards to the reserve provider. Through the use of self-learning techniques the reserve provider can also determine the energy and power constraints, without needing the explicit values from each flexible resource agent, as shown in [6].

B. Definition of Bidladder Bids

The two characteristics that need to be defined in a bidladder bid are (1) the capacity (P_{bid}), and (2) the number of quarter hours the activation of the capacity can be sustained (N_{act}). The determination of the activation price is considered as out of scope in this work. It is assumed that the bids are formed each hour h, for an availibility period from h+1 until h+2. As explained above, the balance gate closure time is assumed at 1 hour before activation. While determining the bids, the possible activation of previous bids (submitted at time h-1) during the time period h until h+1 needs to be taken into account.

Before being able to define the bids, first, a baseline electricity consumption (or production) of the resource portfolio needs to be defined. The baseline consumption indicates what the production of the portfolio of flexible resources is when no activation of reserves takes place. Different approaches for determining this baseline exist [8]. In this work the author opted for a baseline electricity consumption (E_{base}, in [MWh])

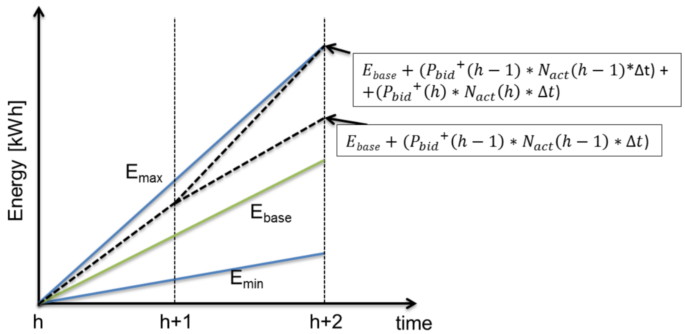

Fig. 2. Schematic illustration of the optimal bid constraint.

that is determined as the average of the E_{min} and E_{max} constraints:

$$E_{base} = E_{min} + \frac{(E_{max} - E_{min})}{2} \tag{5}$$

$$P_{base}(t) = \frac{E_{base}(t) - E_{base}(t - \Delta t)}{\Delta t} \tag{6}$$

P_{base} expresses the power associated with the baseline consumption. It is assumed that at every hour h, the baseline consumption during the time period h+1 until h+2 is communicated to the Cell Operator.

Finding the optimal positive bid $(P_{bid}^{+*}, N_{act}^{*})$ requires the reserve provider to solve following optimisation problem (at every hour h):

$$P_{bid}^{+*}(h), N_{act}^{*}(h) = \text{arg max} f(P_{bid}, N_{act}) \tag{7}$$

subject to:

$$N_{act} \in \{1, 2, 3, 4\} \tag{8}$$

$$E_{base}(h+2) + P_{bid}^{+*}(h-1) * N_{act}^{*}(h-1) * \Delta t + P_{bid}^{+} * N_{act} * \Delta t \leq E_{max}(h+2) \tag{9}$$

$$\min(P_{max}[h+1 : h+2] - P_{base}[h+1 : h+2]) \geq P_{bid}^{+} \tag{10}$$

The objective (eq. (7)) expresses that the bid has to be optimised according to a specific function f. The objective function depends on the resource provider and may for example depend on a certain flexibility cost.
The constraint given in eq. (8) expresses that the maximum number of activations (of Δt = 15 min.) within one hour is 4. The constraint in eq. (10) expresses that the maximal positive bid power should not exceed the maximal power capability of the resource portfolio during the availability period. The constraint given in eq. (9) expresses that the consumption of the portfolio should not cross the E_{max}-boundary at time h+2, even if the previous bid $(P_{bid}^{+*}(h-1), N_{act}^{*}(h-1))$ is maximally activated. A schematic example illustrating this constraint is shown in Fig. 2: the energy consumption of the portfolio when the bid is maximally activated, indicated with the dashed line, should not exceed the E_{max} boundary.

An analogous optimisation problem can be formulated to obtain the optimal negative bid $(P_{bid}^{-*}, N_{act}^{*})$:

$$P_{bid}^{-*}(h), N_{act}^{*}(h) = \text{arg max} f(P_{bid}, N_{act}) \tag{11}$$

subject to:

$$N_{act} \in \{1, 2, 3, 4\} \tag{12}$$

$$E_{base}(h+2) - P_{bid}^{-*}(h-1) * N_{act}^{*}(h-1) * \Delta t + P_{bid}^{-} * N_{act} * \Delta t \geq E_{min}(h+2) \tag{13}$$

$$\min(P_{min}[h+1 : h+2] - P_{base}[h+1 : h+2]) \leq P_{bid}^{-} \tag{14}$$

It is important to note that these optimisation problems can be solved using only the information gathered at the constraint aggregation step. No flexible resource specific details need to be known at the reserve service provider level. This reduces the computational constraints at resource level, and also enables scaling of the approach. The optimisation only requires *aggregated* flexibility constraints, and is independent from the number of flexible resources available within the portfolio.

C. Real-Time Control Step

At every 15 min. timestep the reserve provider may receive a reserve activation signal. The reserve needs to be activated with respect to the submitted baseline consumption. The necessary overall energy consumption for the next timestep has to be dispatched over the different resources within the portfolio. For this a market-based multi-agent system is used [9]. Every flexible resource is represented by an agent which submits a bid function to a virtual energy market. The bid function represents consumed or produced power versus price. The price is a virtual measure indicating the necessity to consume or produce energy. The minimum and maximum power in the bid function correspond to local comfort and safety settings of the associated flexible resource. The reserve service provider is represented by a constant bid function, the power of this bidfunction indicates what the overall consumption of the portfolio needs to be during the next timestep. The bid functions of the flexible resources and the service provider are matched to obtain a clearing price, this clearing price is broadcasted to the different resources. Each flexible resource starts consuming/producing at the power corresponding to the clearing price of its bidfunction during the next timestep.

IV. Simulation Example

To illustrate the proposed control system, a simulation example was carried out. In this example, the portfolio of the restoration reserve provider consists of 1000 batteries, each having a capacity of 10kWh, a charging power of 2 kW and a discharging power of -2 kW. The initial state of charge of the batteries is randomly set between 0 and 100%.

Each hour, the restoration reserve provider submits the negative and positive reserve capacity of his portfolio to the system operator. In the example, each hour either the

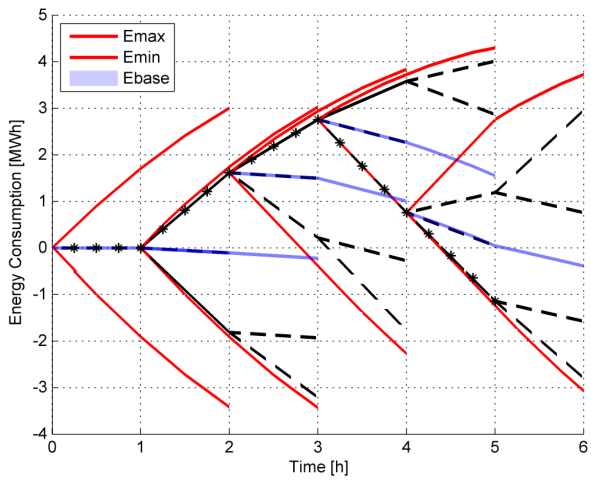

Fig. 3. Schematic illustration of the optimal bid constraint. The red lines indicate the projected E_{max} and E_{min} boundaries at each hour. The blue line indicate the projected baseline consumption. The *-marked line is the actual portfolio consumption. The dashed lines show what the projected energy consumption would be if the maximal reserves would be activated.

maximal positive or the maximal negative reserve capacity is activated for the maximal duration. Positive or negative capacitive activation was determined randomly.

In this example it is assumed that the objective function is to maximise the amount of energy that has been bid. Fig. 3 illustrates the energy consumption constraints the service provider needs to take into account each hour while determining the optimal reserve capacity. The aggregated E_{max} and E_{min} boundaries for the following 2 hours of the portfolio are shown in red. These are recalculated each hour based on the updated boundaries communicated by the individual batteries. The individual E_{max} and E_{min} boundaries depend on the state of charge of the battery, and its charging/discharging power. The baseline energy consumption projected for the next two hours at each hour is shown in blue. As discussed above, the projected baseline consumption is assumed to be the average of the E_{max} and E_{min} boundaries.

The actual energy consumption (baseline + reserve activation) is shown by the *-marked line. The dashed lines indicate, similarly as in Fig. 2, the projected energy consumption if the maximal reserve capacity would be activated for the next hour. The projected maximal consumption if the determined optimal bid is activated is also shown. Fig. 4 shows the determined optimal reserve capacity bids for each hour. As can be seen, the maximal number of activations at each hour is always 4 (both for negative and positive reserve bids). The bid capacity varies, and depends on the projected energy and power boundaries.

Each 15 min. the portfolio needs to consume a certain power: the baseline power increased/decreased with the requested reserve power. As discussed above, an agent-based market-based system is used to control the real-time dispatch of the requested power demand. Each 15 min., each battery submits a power-price bidfunction to the restoration reserve

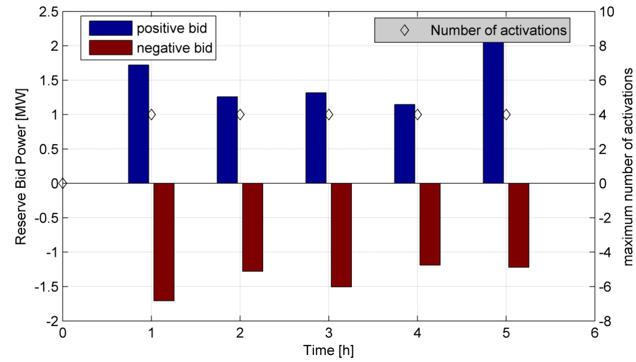

Fig. 4. The optimal reserve capacity bids determined each hour. The positive and negative capacity bids are shown, as well as the maximum number of 15. min activations.

provider. This is calculated as follows:

$$bid = P_{max} + (P_{min} - P_{max}) * price \tag{15}$$

with P_{max} and P_{min} the maximal possible charging, resp. discharging, power during the next 15 min. These values depend on the battery state of charge as follows:

$$P_{max} = min((1 - SoC) * Capacity * 4, P_{maxcharge}) \tag{16}$$

$$P_{min} = min((-SoC) * Capacity * 4, P_{discharge}) \tag{17}$$

As an illustration, Fig. 5 shows the aggregated bid of the overall portfolio at a specific quarter hour during the simulation, combined with the bid composed by the reserve provider. The latter is a fixed-power bid, with the power indicating the requested power consumption. The crossing point of both bids indicates the clearing price, which is broadcasted to the overall portfolio. Fig. 6 shows the actual power consumption by the portfolio at every 15 min. timestep (in blue). The difference between the activated and the requested power consumption is shown in black. As can be seen, this difference never exceeds 4e-4 MW in the shown example. As an illustration the baseline power consumption is also shown in the plot. The difference between baseline and actual power consumption indicate the reserve power that was activated.

V. Conclusions and Future Work

This work proposes a control system for restoration reserve providers in which optimal biddings of restoration reserve capacity are made based on the predicted flexibility of the reserve resources within the portfolio of the reserve provider. The reserve capacity bids need to be formed so that activation of the capacity is always feasible. The determination of the optimal reserve capacity bids is based on aggregated flexibility constraint information received by the individual flexible resources. No further resource-specific information is used to determine the optimal reserve capacity bid. It is

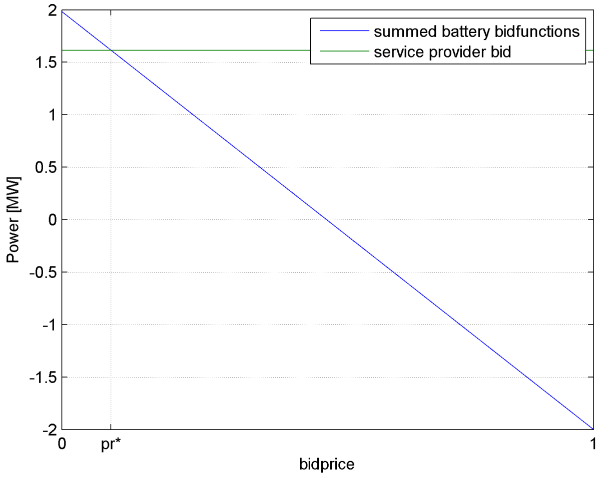

Fig. 5. Real-time control power vs. price bids: aggregated portfolio bid function and reserve provider bid. The clearing price $pr*$ is also indicated.

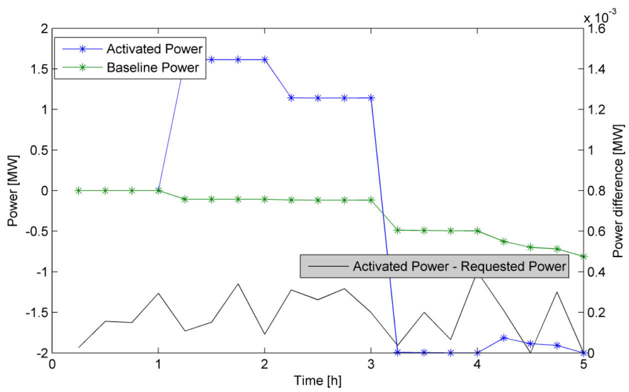

Fig. 6. Schematic illustration of the optimal bid constraint.

assumed that the gate closure time for submitting reserve capacity bids is 1 hour before activation time. The activation and dispatch of the required power consumption at real time is done through a market-based multi-agent control system. A simulation example, in which the reserve capacity of a portfolio of batteries is simulated, proves the feasibility of the proposed approach and shows that a sufficient precision of the portfolio response can be obtained.

Further work includes the introduction of different types of flexible resources, and bringing the developed control system to a lab test environment.

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