# Market Response for Real-Time Energy Balancing: Simulation using Field Test Data

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***Abstract*—Maintaining the balance between load and generation is crucial to power system stability. Automatic Frequency Restoration Reserves (aFRR) are activated to cope with any imbalance occurring in each Control Area (CA). Other than that, European countries pursue different balancing strategies. Incentivizing market response for real-time energy balancing is a promising balancing strategy, which is applied in the Netherlands and Belgium and is referred to as Passive Balancing (PB). Advantages are reduced demand and costs for aFRR and additional business cases for Balance Responsible Parties (BRPs). The system imbalance and the imbalance price are published close to real-time, enabling BRPs to support the balancing process by optimizing their consumed and generated power. This study addresses the implementation of PB in Germany by simulating the contribution of four real BRPs using measured field test data and object oriented programming.**

***Index Terms*—Load management, Power Market, Market Opportunities, Power System Simulation**

## I. Introduction

The balance between load and generation in a power system is to be kept at any time. The purpose of automatic Frequency Restoration Reserves (aFRR) is the elimination of unscheduled power flows between Control Areas (CAs) in the synchronous grid of Continental Europe [1]. The activation of aFRR is the responsibility of each CA, which are to fully compensate their imbalance with aFRR within 15 minutes at the latest [2]. Each CA is divided up into Balance Responsible Parties (BRPs). Each BRP trades the amount of energy they plan to generate and consume within each Imbalance Settlement Period (ISP) beforehand at the day-ahead and intraday markets. By that, a schedule is defined for the BRP and the respective ISP. During grid operation, certain schedule deviations occur due to e.g. load noise or forecast errors. The sum of schedule deviations of all BRPs of a CA defines the Area Control Error (ACE), i.e. the total imbalance of the CA and which is to be compensated by aFRR.

The CA of Germany coordinates the activation of balancing power of certain aFRR providers, which are paid for their service following the pay-as-bid principle [3]. The costs for aFRR are allocated to the BRPs according to their respective schedule deviation [4]. Depending on the arithmetic sign of the deviation and the aFRR costs, this can imply costs or income for a BRP, indicating, if their deviation worked to the advantage of the total ACE or not. In principle, BRPs have a financial incentive to deviate from their schedule, as long as it implies a reduction of the ACE. In real-time operation, a BRP generally has no means of predicting, if their schedule deviation will lead to costs or income, since the publication of aFRR costs takes place after the end of an ISP.

The idea of Passive Balancing (PB) is to provide BRPs with certain information during an ISP enabling them to estimate the financial consequences of their current schedule deviation. By that, each BRP can actively decide to resolve, to keep, or even cause a deviation according to the implied financial incentive. This effectively enables BRPs to reduce the aFRR demand and costs for the CA while their own imbalance costs are optimized [5]. Studies show that certain BRPs in Germany already actively manipulate their schedule deviations to generate profit [6], although they are legally prohibited to do so [7]. On the one hand, this implies a non-transparent and unequal market for BRPs. On the other hand, the situation can lead to significant disincentives for BRPs and escalating imbalances and aFRR costs due to non-transparency [6]. In addition, the pay-as-bid pricing in balancing energy markets has been discussed controversially [8]. It has been shown to favor a certain bidding behaviour that results in escalating prices and collusion in the German CA [3]. The concept of PB has already been implemented into the energy markets of Belgium and the Netherlands. The transparent real-time markets feature minimized use of aFRR energy as well as low and steady aFRR costs [9].

This study addresses the potential implementation of PB in the German CA. In the context of the research project *Norddeutsche Energiewende 4.0* (NEW 4.0) a field test was conducted in November 2019, testing a number of progressive ancillary services in grid operation. Four BRPs, that participate in the project, indicated their interest in providing PB during the field test. Due to technical limitations, no real-time information could be provided as a decision making

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basis for the BRPs. Their real-time market response is simulated in retrospect and presented in this study. The impact of the four BRPs on the total aFRR demand and costs of the German CA are simulated, while showing the financial consequences for each BRP, if they provided PB during the field test.

An introduction to the basic guidelines for aFRR and their cost calculation method for the German energy market are described in sections II-A and II-B, whereupon the simulation setup is presented in section II-C. An initial simulation to verify the model is described in section III. The actual implementation of PB into the model is shown in section IV. The simulation results are presented in section V, before section VI discusses the results and possible applications of PB.

## II. Method and Modelling

The modelling and simulation approach is described in this section. The principles of aFRR, which the model is based on are outlined in section II-A, followed by the specific aFRR cost calculation procedure of the German CA in II-B. The object-oriented modelling approach then is described in section II-C.

### A. Secondary Controller in a Control Area

The ACE of a CA is the sum of all schedule deviations of its BRPs and hence equals the sum of all unscheduled load flows across the borders of the CA [2]. In a CA with $n$ BRPs the ACE thereby is defined as

$$G = \sum_{i=1}^{n} P_{sc,i} - \sum_{i=1}^{n} P_{gen,i} - \sum_{i=1}^{n} P_{load,i} + K_r \Delta f, \qquad (1)$$

with the scheduled, generated, and consumed active power of the $i$-th BRP $P_{sc,i}$, $P_{gen,i}$ and $P_{load,i}$, the frequency deviation $\Delta f$, and the frequency characteristic $K_r$ of the CA [2]. The ACE signal is processed close to real-time and is the input of the Secondary Controller (SC) of the CA. The SC is a Proportional Integral (PI) controller, in which the correction variable

$$\Delta P_d = \beta G - \frac{1}{T_r} \int G \mathrm{d}t, \qquad (2)$$

is the output of the SC, while the parameters $\beta$ and $T_r$ are the proportional gain and the integration time factor of the SC, respectively [2]. The signal $\Delta P_d$ is used to trigger power plants which activate the required aFRR power within the CA. In order to minimize aFRR costs, CAs use two separate Merit Order Lists (MOLs) for positive and negative balancing power, respectively [10].

### B. Control Area of Germany

The German power system is subdivided in four CAs. Since 2010, the four CAs have been coordinating the activation of aFRR, effectively forming a single CA in terms of aFRR [11]. The reimbursement of aFRR uses pay-as-bid pricing, meaning that for each ISP of 15 minutes, each aFRR provider is reimbursed according to the amount of balancing energy they provided and the exact price claimed in the MOL. Summing up the amounts of aFRR energy and costs of $m$ providers, total amounts of positive and negative aFRR energy and costs can be assigned to each ISP. The imbalance price (*Ausgleichsenergiepreis*–AEP) per ISP is calculated using (3):

$$AEP = \frac{\sum_{j=1}^{m} C_j}{\sum_{j=1}^{m} E_{pos,j} - \sum_{j=1}^{m} E_{neg,j}}, \qquad (3)$$

in which $C_j$ are the costs of provider $j$, and $E_{pos,j}$ and $E_{neg,j}$ are the amounts of positive and negative balancing energy, provider $j$ activated [4]. Due to a singularity in (3) for equal total amounts of positive and negative energy, the AEP escalates in respective cases. For this reason, the AEP is capped by the highest price of a single aFRR provider active in the ISP. Beyond that, the AEP follows four additional steps, each applicable in certain situations, but which are not applied in the simulations of this study. In general, the AEP can be positive or negative at the end of an ISP. It is multiplied by the schedule deviations of each BRP, resulting in costs or income for the BRP, depending on the arithmetic sign of both the AEP and their schedule deviation.

### C. Simulation Environment

Balancing market simulation software is developed in Python and used in this study. The software is set-up using object-oriented programming. Classes for all relevant grid structures including the synchronous zone, CAs, and BRPs are defined to model the hierarchy of these structures within the synchronous zone. A grid model is composed of objects for BRPs that are subordinated to objects modelling the CAs, which in turn are subordinates to an object modelling the synchronous zone. Following this approach, the hierarchy of objects reflects the hierarchy of the actual power system. A schematic illustrating the data and signal flow of the simulation environment and the interaction of the CA and BRP classes is shown in figure 1.

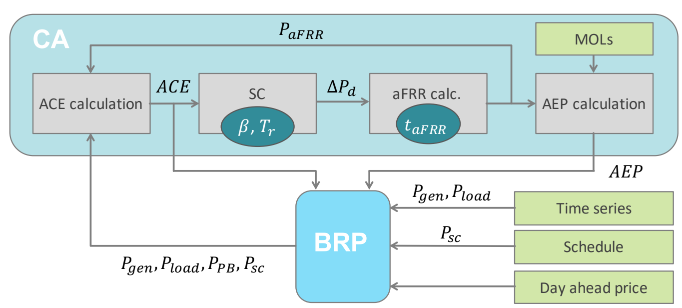


Fig. 1. Schematic data and signal flow of the simulation environment

Time series for the actual and scheduled power generation and consumption of each BRP are to be set-up to serve as input data for the simulation and the basis for the calculation of schedule deviations and activation of aFRR. The ACE is defined in the CA class and is calculated as the sum of schedule deviations of all BRPs, that are subordinated to the CA according to (1). In addition, the CA class is equipped with a discrete PI controller to model the SC and which can be parametrised according to (2). Using a first-in-first-out queue, the output signal of the SC is delayed by a parametrisable time constant, to model the response time $t_{aFRR}$, aFRR providers take to actually activate the balancing power $P_{aFRR}$ according to the requested power $\Delta P_d$. Further, the CA class contains MOLs and methods calculating the aFRR costs as described in section (II-B). The principles of aFRR activation and cost calculation are intrinsic to the grid model due to the hierarchy of objects.

The PB mechanisms are implemented in the BRP class. First, the currently available potentials to provide positive and negative PB power are calculated continuously according to the current power consumption $P_{load}$ and power generation $P_{gen}$ and their specific upper and lower power limits. Each BRP object is provided with the ACE and AEP signals in real-time and the day-ahead price for each ISP. Using this information, BRPs can predict the financial outcome of their schedule deviation. Specific decision making rules for the provision of PB are implemented for each BRP object, which reacts by providing Passive Balancing power $P_{PB}$, according to the current potentials and decision making variables. The activated PB power of a BRP object implies an alteration of their schedule deviation. As a result, the schedule deviation of the CA is altered, affecting the activation of aFRR.

## III. Model Verification

Before simulating the PB provision of the participating BRPs, a model verification is presented in this section. To verify the model and to create comparison data for the following simulation, the field test is simulated without PB. The field test conducted in the NEW 4.0 project started on November 18th 2019 at 00:00 and ended November 24th at 23:59. The aim of the model verification is to simulate aFRR provision and costs during this week and to compare the results with historic data. For that purpose, only one BRP object without potential PB provision is implemented in the CA of Germany. The historic ACE [12] of the field test week is implemented as the power generation $P_{gen}$ of the BRP object, while its schedule is set to zero. By that, the time series represent the ACE of the CA in the model. The SC parameters $\beta$ and $T_r$ are set according to grid code requirements [13]. The response time $t_{aFRR}$ is set to the minimum requirement of 30 s for aFRR [2]. Furthermore, the historic MOLs of the field test week are provided [14] and updated every 4 hours for a realistic calculation of the AEP. Table I shows the correlation factors between simulated aFRR power and aFRR costs with historic time series [15]. The historic and simulated AEP are shown for an exemplary day of the simulation in figure 2.

TABLE I
Correlation between simulated and historic time series

| aFRR direction | aFRR power | aFRR costs |
|---|---|---|
| **Positive** | 0.987 | 0.982 |
| **Negative** | 0.993 | 0.926 |

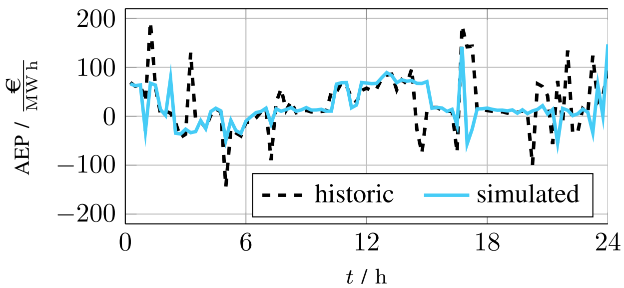

Fig. 2. Historic and simulated AEP for an exemplary day

The simulated and historic aFRR time series have a strong correlation. the AEP calculation in the model is less accurate, as a correlation factor of 0.525 indicates. Possible reasons are the simplified calculation method for the AEP, as described in section II-B and the fact that imbalance netting mechanisms are neglected in the simulation. In general, the historic data shows a more fluctuating AEP and higher extrema. The average positive historic AEP equals $59.42\,€/\mathrm{MWh}$ for the field test, while the average negative AEP is $-40.05\,€/\mathrm{MWh}$. The average simulated values amount to $52.29\,€/\mathrm{MWh}$ and $-32.89\,€/\mathrm{MWh}$. Further, it can be noted that occasionally the simulated AEP has the opposite sign of the historic AEP, which is related to the singularity in (3). Nevertheless, the accuracy of the model is considered sufficient to evaluate market response for real-time energy balancing with the field test simulation.

## IV. Field Test Simulation

Four BRPs participating the NEW 4.0 project provided data enabling the implementation of their PB potentials and decision making processes into BRP objects. The BRP models are added to the grid model, as described in section III, to simulate their PB provision during the field test week. The provided data and deducted implementation of the BRPs is described in section IV-A. A description of the field test simulation, that was executed is given in section IV-B.

### A. Implementation of Field Test Participants

The provided data contains the consumed and generated power of the four BRPs in high time resolution as well as the schedules for all ISPs of the field test week. Further, certain potentials for adjusting their loads and generators as well as possible ramp rates were communicated.

Three of the BRPs operate large-scale industrial loads in production, which can increase or decrease their consumed power to a certain degree without disturbing the production process. The BRPs have potentials to provide positive or negative PB power accordingly. The fourth BRP operates several wind farms with a combined rated power above $2500\,\mathrm{MW}$. The turbines can decrease their power output down to $10\,\%$ of their power rating and provide negative PB power accordingly. Both the loads and wind turbines can change their operating point quickly resulting in fast activation of the PB potentials.

TABLE II
COMBINED PB POTENTIALS FOR THE FIELD TEST

| PB direction | Max. PB power | Max. ramp rate |
|---|---|---|
| **Positive** | 80.0 MW | 80.1 MW $s^{-1}$ |
| **Negative** | −2517.6 MW | −249.4 MW $s^{-1}$ |

The combined PB potentials and ramp rates of the four BRPs are shown in table II.

Regarding the decision making process, the four BRPs gave detailed information. For the actual provision of PB they would have to consider a large number of variables including commodity prices and their order situation. For this reason, certain assumptions and simplifications were made for the simulation, presumably resulting in a certain tendency to overestimate the current PB potentials. The implemented decision making is limited to the real-time ACE and AEP signals as well as the day ahead price. Accordingly, some BRP objects simply activate PB power, as soon as the AEP exceeds certain thresholds. Others consider both the AEP and the day ahead price to estimate the financial outcome of PB provision. However, all BRPs limit their total PB power to the magnitude of the ACE at any time, as they could otherwise solely overcompensate the total imbalance of the CA, which would be an unreasonable behaviour under any circumstance.

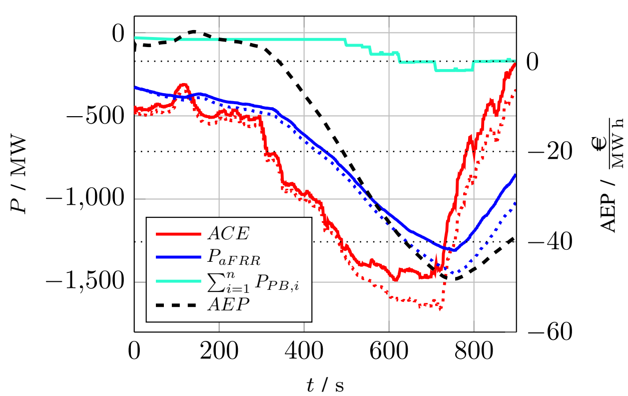

Fig. 3. Activation of PB over one ISP

## B. Execution of Field Test Simulation

The same week described in section III is simulated again using the same simulation input for the CA including the historical data of the ACE and parametrisation of the SC. For this simulation, five additional BRP objects are added to the grid model, four of which represent the BRPs participating in the field test. Time series for the scheduled, consumed and generated power are added to these BRP objects to simulate their schedule deviations, as they actually occurred during the field test. These additional schedule deviations imply a certain alternation of the total power balance and ACE of the CA in the simulation. In order to compensate this effect, a fictional fifth BRP is added, that precisely mirrors the combined load, generation, and schedules of the other four BRPs. Accordingly, the sum of consumed power of the four BRPs at any given time step appears as the generated power of the fictional BRP, while the sum of scheduled generated power appears as a schedule for consumed power in the fifth BRP and so forth. This way, the actual schedule deviations of the four BRPs during the field test do not alter the total power balance and schedule deviation of the CA as simulated in the verification simulation, which can therefore be used as a point of reference. The time series for scheduled, consumed and generated power of the four participating BRPs are also used to dynamically calculate their PB potentials for each time step. According to the PB potentials and the price signals, the four BRPs provide PB, as described in section II-C. By activating PB power and thereby modifying their schedule deviations, the four BRPs alter the total deviation of the CA and contribute to power balancing.

# V. SIMULATION RESULTS

In the simulation, the real-time AEP signal fluctuates between a maximum value of 620.51 €/MWh and a minimum value of −614.10 €/MWh, inducing the activation of certain amounts of PB in all four BRPs. By that, the BRPs contribute to the power balancing of the CA significantly. As outlined in section IV-A, the simulated PB potentials are expected to be greater than the potentials in reality. On the other hand, the simulated AEP shows a steadier behaviour as the historic data, as shown in section III. The result of the latter being a more moderate use of mentioned PB potentials. To illustrate the mechanics at hand, figure 3 shows the simulation results for the ACE, the balancing power of aFRR and PB, and the AEP signal for an exemplary ISP. The dotted graphs show the respective results of the model verification simulation, in which no PB was applied.

During the initial 300 s of the ISP, the simulated AEP signal fluctuates around approximately 18 €/MWh, inducing an incentive for PB provision for certain BRPs, which respond by activating around −38 MW of negative balancing power. This leads to a reduction of the absolute schedule deviation of the CA, as the ACE graphs indicate, and which results in a reduction of aFRR power. Around $t = 500$ s the AEP signal drops below −20 €/MWh, which induces further activation of negative PB power, until a maximum of −227.87 MW is provided at $t = 711$ s. Over the whole ISP, the four BRPs provide −23.66 MW h of balancing energy, by which the activated negative aFRR energy is reduced by 15.78 MW h. The implied imbalance costs drop by 27.2 % to 7381.74 €.

Over the whole week, both positive and negative aFRR energy and costs are reduced. A summary and comparison of the simulation results is given in table III. By applying PB, the total activated positive aFRR energy is reduced by 287 MW h. Due to the large potentials for negative PB, the amount of negative aFRR is reduced by 883 MW h. The total aFRR costs of the week are reduced by 57 354 € for the German CA. On the other hand, the four BRPs can optimize their imbalance costs significantly. Using the simulated AEP for each ISP the imbalance costs of the four BRPs amount to 54 880 € for the week. Calculating their imbalance costs using historic AEP

TABLE III
SIMULATION RESULTS COMPARED TO THE REFERENCE SIMULATION

| | without PB | with PB | Rel. change |
|---|---|---|---|
| **Pos. aFRR energy** | 16.2 GW h | 15.9 GW h | −1.77 % |
| **Neg. aFRR energy** | −19.4 GW h | −18.5 GW h | −4.56 % |
| **Pos. aFRR costs** | 1.342 M€ | 1.299 M€ | −3.19 % |
| **Neg. aFRR costs** | −0.217 M€ | −0.231 M€ | −6.74 % |
| **Pos. PB power** | – | 387.7 MW h | – |
| **Neg. PB power** | – | −983.7 MW h | – |
| **total AEP costs** | 54 880 € | 9968 € | −81.84 % |

data and the simulated schedule deviations results in 73 951 €. By manipulating their schedule deviations, the BRPs can lower the simulated imbalance costs by 81.84 %. Three of the BRPs can even turn their imbalance costs into income.

However, looking at certain ISPs, in which the AEP signal particularly fluctuates, shows that the PB mechanisms, as they are applied, can lead to decisions, that result in higher imbalance costs for single BRPs at the end of the ISP. The response of a single BRP during an exemplary ISP is shown in figure 4.

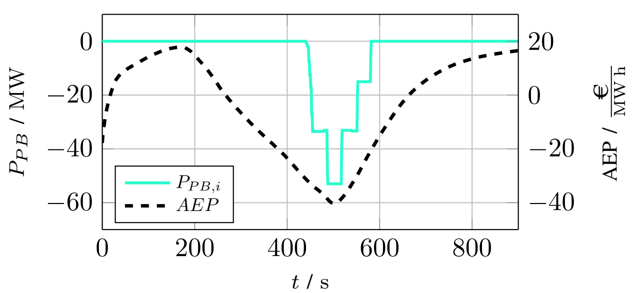

Fig. 4. Activation of PB of a single BRP

During this ISP, the AEP signal fluctuates between a maximum of $17.78\,€/\mathrm{MWh}$ and a minimum value of $-40.31\,€/\mathrm{MWh}$, crossing the zero line three times. From $t = 441\,\mathrm{s}$ to $t = 582\,\mathrm{s}$ the signal induces the activation of negative PB power for the BRP, which provides a total of $-1.228\,\mathrm{MW\,h}$ of balancing energy until the end of the ISP. The AEP converges towards the final value of $16.51\,€/\mathrm{MWh}$ at the end of the ISP. Thereby, the additional schedule deviation of $-1.228\,\mathrm{MW\,h}$ leads to additional imbalance costs of $20.28\,€$ for the BRP for this particular ISP. Analogous ISPs, in which a fluctuating AEP signal leads to adverse provision of PB for single BRPs, can be observed frequently in the field test simulation results. Overall, ISPs, in which BRPs can in fact optimize their imbalance costs, prevail. Hence, providing PB leads to lower imbalance costs for each of the four participating BRP over the course of the week.

## VI. CONCLUSION AND OUTLOOK

This study addresses the implementation of PB in the German CA by simulating the real-time market response of four BRPs during a field test. Using detailed information and data provided by the BRPs, their potential provision of balancing power during the field test was simulated. The results indicate, that both the German CA and the BRPs could benefit from the implementation of PB in Germany. The amounts of positive and negative aFRR energy as well the aFRR costs could be lowered, while new business cases for the BRPs arise, enabling them to purposefully use their schedule deviations to minimize imbalance costs or even actively generate income.

However, the simple decision making rules based on the continuously calculated AEP signal can lead to adverse behaviour of BRPs and to an increase of their imbalance costs for certain ISPs. As the simulation results show, the risk of adverse behaviour is particularly high for ISPs, in which the AEP signal fluctuates particularly. Especially due to a singularity in the calculation method of the AEP, its behaviour is highly unstable in certain situations and especially in the beginning of an ISP. A possible implication being that in a PB market using the AEP signal as simulated, BRPs should interpret the signal as a prediction and be careful with manipulating their schedule deviations unless the signal is stable and unambiguous. A second implied solution being, that the AEP signal itself can be improved to be more reliable by e.g. applying low pass or moving average filters or be replaced altogether for a more stable PB response. These approaches are subject to future studies.

In grander scope, this study points out the complex imbalance price calculation method to be a problematic characteristic of the German energy balancing market. In a context of other studies regarding the obligation for BRPs to keep their schedule or the pay-as-bid pricing for aFRR, this study further indicates that reforming the existing German energy balancing market is expedient. Changes including a transparent imbalance price and the implementation of PB can lead to improved system stability, steadier prices and lowered costs for balancing energy.

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