Market Response for Real-Time Energy Balancing with Fuzzy Logic

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***Abstract*—Market response for real-time energy balancing is a promising tool for power balancing: Smart Balancing. Transparency about the balance and imbalance price in the control area incentivizes market response. Market participants benefit from real-time business cases in addition to energy and balancing products. Fuzzy logic is introduced to optimize revenues for market participants with minimal risk. Market response (with fuzzy logic) is simulated with marginal vs. pay-as-bid clearing mechanisms and single vs. dual imbalance pricing. Single imbalance pricing can lead to overcompensation. This requires an additional rule to meet the Smart Balancing definition. Smart Balancing is present with a combination of single and dual pricing.**

***Index Terms*—Power Balancing, Real-Time Market, Passive Balancing, Fuzzy Logic**

I. INTRODUCTION

Maintaining the balance between power generation and load in a control area is a system requirement. Power balancing aims for a stable system frequency and prevents unscheduled power flows between neighboring control areas. Power balancing is organized by grid operators who organize balancing markets and control the contracted units. Market response is an additional tool to cope with imbalances in a control area by creating an additional business case for market participants. The area control error (ACE) and the imbalance price are published close to real-time. This information enables market participants to optimize their generation and consumption in real-time to support the balancing process. Market response is aiming to reduce the imbalance within a control area and generate profit via the imbalance price. This leads to reduced demand for Frequency Restoration Reserves (FRR) and saves costs.

The concept of market response for real-time energy balancing is widely discussed in the literature [1], [2], [3]. For example as "Smart Balancing" which is defined as "a set of measures to avoid the activation of FRR by market parties who create schedule deviations. Smart Balancing is incentivized by correct imbalance pricing in combination with public real-time information. Correct pricing does not incentivize overcompensation." [4]

Smart Balancing is currently incentivized by public real-time information in the Netherlands and Belgium. However, this approach involves uncertainty for the grid operators, as they predict network conditions based on scheduled power flows. Before such a concept can be implemented in other countries, its effects must be assessed. For this purpose, it is important to identify potential market participants and to predict their behavior.

This study presents fuzzy logic as possible approach for the decision-making process of market participants with regard to the Smart Balancing definition and the German energy market. The imbalance price as existing incentive and the area control error as indicator for the risk of a changing imbalance price are investigated as input parameters. The clearing schemes marginal and pay-as-bid clearing as well as the pricing schemes single and combined single and dual pricing were analyzed. For that reason, fuzzy logic as a method to optimize financial benefits at minimized risks is introduced and a suitable set-up is presented.

The following research questions are addressed: What kind of information is used and needed by market participants to optimize their portfolio in real-time? Is fuzzy logic a suitable tool to predict and optimize market responds? Which fuzzy logic set-up optimizes financial benefits at minimized risks and what are relevant tuning parameters? The analysis is organized in three-steps:

1) Analysis of relevant input data, considering market design options pricing and clearing scheme. (Section II)
2) Introduction of fuzzy logic as method for decision making. Definition of the fuzzy logic set up to optimize financial benefits at minimized risks for market participants. (Section III)
3) Simulation of test scenarios to evaluate fuzzy logic based market response under varying conditions. (Section IV)

II. ENERGY MARKETS AND SMART BALANCING

In the first place, power generation and load is dispatched at energy markets; prices are determined and schedules are created. All market participants shall keep to their schedule. In real-time, summing up all (positive AND negative) schedule deviations results to the (positive OR negative) ACE which

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This paper was developed within the project NEW 4.0 (North German Energy Transition 4.0) which is partly funded by the German Federal Ministry for Economic Affairs and Energy (BMWI). *(sponsors)*

is compensated by FRR. Thus, the ACE can be reduced by additional schedule deviations in the correct direction. Market participants can achieve financial benefits, if the imbalance price exceeds their marginal costs. Potential financial benefits are, thus, determined by the imbalance price. The risk is, that excessive real-time market response could result in overcompensation of the ACE and change the imbalance price.

Market response is a combination of technical and financial optimization. This section compares different market design options and its influence on the decision-making process. A previous study identified six relevant design parameters for market response: Imbalance settlement period, publication of data, full activation time of reserves, balancing service pricing mechanism, activation strategy and imbalance pricing mechanism [5].

The imbalance settlement period is assumed to be 15 minutes in the following discussion, as defined in the EU regulation [6]. The full activation time of reserves and the activation strategy are not considered and shall be subject to future research. Considered market design options are (A) transparency, (B) single vs. dual imbalance pricing and (C) marginal vs. pay-as-bid clearing scheme. Furthermore, (D) the potential decision-making process is discussed.

A. *Design option - transparency*

Smart Balancing is achieved by correct imbalance pricing in combination with public real-time information. From historical data can be seen, that financial opportunities of the imbalance price (between -324 EUR/MWh and 2130 EUR/MWh) did exceed the financial opportunities at the day-ahead market (between -90 EUR/MWh and 122 EUR/MWh) [7], which shows the already existing incentive for market response. Provided information shall, therefore, include the ACE in MW and the imbalance price in EUR/MWh.

B. *Design option - single vs. dual imbalance pricing*

Market response is a reaction to the imbalance price. The ACE is only considered, because it indicates the risk of a changing imbalance price. In the regarded countries there are two common imbalance pricing mechanisms, single and dual pricing. Single pricing means that the costs of all balancing energy activated within the imbalance settlement period are added up to one price, regardless of their sign. This results in three scenarios for a balancing group: In the case of schedule adherence, the price has no relevance, in the case of a deviation with the imbalance of the control area, costs are incurred, and in the case of a system-related deviation, a compensation is paid. With dual pricing, one price each for positive and negative balancing energy is applied. This means that each deviation is paid for and the option of remuneration is no longer applicable. The Dutch use a combined approach, hereinafter referred to as combined pricing. They consider whether or not there was a change in the sign of the activated balancing energy within the imbalance settlement period. In periods without a change of sign, the single price is applied and systemic deviations are rewarded. In periods with sign change, the dual price is applied and all deviations are penalized.

C. *Design option - marginal vs. pay-as-bid clearing scheme*

The risk of a changing imbalance price depends on the market mechanism and clearing process. They can significantly determine the behavior of market participants and their influence on the overall system. It is therefore important to take these mechanisms into account in the decision-making process. The clearing schemes under consideration are marginal pricing and pay-as-bid. Both clearing schemes use merit order lists (MOL) to calculate the imbalance price. Marginal pricing means that the price for the most expensive activated reserve determines the price for all reserves. With pay-as-bid, the bid of each reserve is taken into account.

D. *Decision-making of market participants*

The decision-making process to participate in Smart Balancing depends on (i) the flexibility potential, (ii) the potential income and (iii) the associated risk.

(i) In real-time, the technical flexibility potential of a market participant is of physical nature. It is asset-specific and must be determined individually for each asset of the market participant. It depends on the overall system state (positive or negative imbalance) and the available flexibility. Available flexibility is calculated taking the operational state of each asset into account. The features maximum possible ramp, maximum full load hours and, if applicable state of charge define the technical potential. The economic flexibility potential describes that part of the technical potential of which marginal costs are covered by the imbalance price in real time. It would therefore generate profit.

(ii) The day-ahead market price (represents the benchmark price for power) and the imbalance price (represents the real-time price for power) are of interest for the economical potential. The market response of any market participant results from a variety of factors, such as the spread between day-ahead price and imbalance price and the deviation between real-time and scheduled consumption and generation.

(iii) In case of single imbalance pricing or a combination of single and dual imbalance pricing, the risk of a changing sign of the imbalance price is of mayor interest, as well. The next section introduces fuzzy logic to control market response, which considers this risk parameter in competition to the financial incentive.

III. FUZZY LOGIC

The decision-making of market participants is anticipated to optimize market response. Fuzzy logic shall optimize the financial advantage. Therefore, this section examines how individual participants would optimize their opportunities within different regulatory frameworks. Fuzzy logic optimizes market response by analyzing financial opportunities and judging risks. Relevant inputs for the fuzzy logic are described. The membership functions and the associated rules are defined and the framework in which fuzzy is embedded to represent the decision-making process is explained.

A. Fuzzy environment

Market response to real-time information is determined by (i) the economic flexibility potential, (ii) the potential income and (iii) the risk of changing imbalance price as described in Section III. Market participants calculate (i) the economic flexibility potential, which corresponds to the maximum possible response. The fuzzy logic determines the optimal response based on (ii) the potential income and takes (iii) the risk into account. Flexible assets get that new set-point and ramp up or down according to technical limitations.

Fig. 1 illustrates the fuzzy environment, which is used to optimize market response for real-time energy balancing. The steps to be executed by market participants are:

1) Calculate economic flexibility potential: All existing technical potential is ordered by marginal costs. The marginal costs, the day-ahead price and the imbalance price define the economic flexibility potential.
2) Identify optimal activation ratio: Market-design, the potential income and the power imbalance are used as input variables for the fuzzy logic, since they define the potential financial benefit and risk of market response.
3) Market response: The economic potential is multiplied by the activation ratio. The resulting power is to be activated as market response. In the present simulation the ramp of the technology is considered.

B. Input - potential income

The fuzzy logic is called with the potential income as input variable. Marginal costs have to be identified by the market participant first, to be compared to the imbalance price. Data should include all available flexibility and its marginal costs. The day-ahead market price is the benchmark price at the current period. It can influence the economic potential in different manners.

$$Income = ImbalancePrice - Costs \tag{1}$$

C. Input - risk indicator

The difficulty of risk assessment lies in anticipating the behavior of other market participants. Fuzzy logic is used to optimize and predict the relative Smart Balancing contribution based on limited knowledge about the current and future behavior of other market participants.

1) Risk with single pricing: For single pricing, the average $\text{ACE}_{\text{average}}$ is used to predict the risk that the single price change the sign. A positive imbalance over 15 minutes (upward reserves dominated) leads to a positive imbalance price (additional generation and reduced load is rewarded). A negative imbalance over 15 minutes (downward reserves dominated) leads to a negative imbalance price (additional load and reduced generation is rewarded).

$$ACE_{average} = \frac{\int ACE}{t} \tag{2}$$

2) Risk with combined pricing: As described in Section III, a combination of single and dual imbalance pricing is another market design option. In this case, the ACE itself is used to predict the risk of changing to a dual imbalance pricing scheme. This would involve a changing sign for the applied imbalance price.

D. Introduction of membership functions

Fuzzy logic classifies input data by membership functions and then relates them via rules. To set up a fuzzy controller, the relevant input data, including their minimum and maximum values and the distribution of the data, are required. Suitable values are derived from historical data of the German energy market in 2019, summarized in table 1. Fig. 2 illustrates the membership functions of ACE and $\text{ACE}_{\text{average}}$, used as risk indicators of a changing sign of the imbalance price.

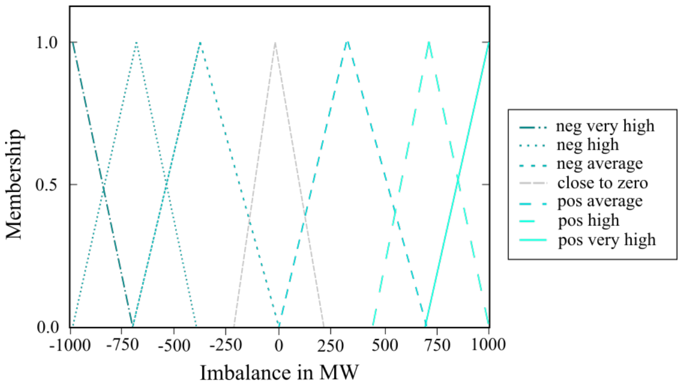

Fig. 2. Membership functions of input variable imbalance in MW

Membership functions are also assigned for the net margin as further input. Values between zero and 100 EUR/MWh are

TABLE I

FINANCIAL OPPORTUNITIES IN GERMANY 2019, DATA FROM [7]

2019	Day-Ahead Market	Imbalance Price	ACE
Average	37.7 EUR/MWh	39.2 EUR/MWh	117.4 MW
St. deviation	15.5 EUR/MWh	51.1 EUR/MWh	106.3 MW
Min	-90.0 EUR/MWh	-323.9 EUR/MWh	0.0 MW
Max	121.5 EUR/MWh	2130.0 EUR/MWh	1600.0 MW

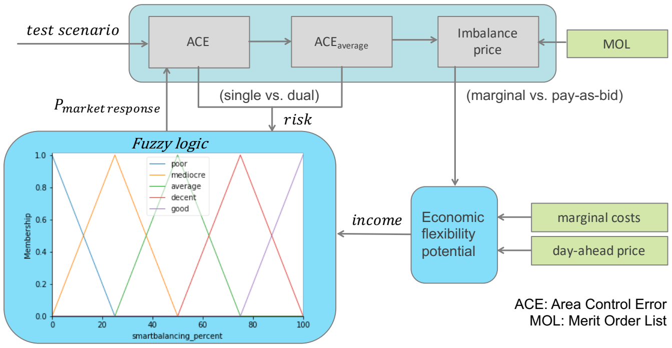

Fig. 1. Environment of fuzzy logic for optimization of market response

assumed as relevant net margin. The fuzzy output is expressed as a percentage between zero and 100. The membership functions of netmargin and fuzzy output are defined by dividing their value range into five equally distributed gradations named poor, mediocre, average, decent and good.

E. Introduction of fuzzy rules

Besides the input data and their classification in membership functions, knowledge of the relationship between the parameters is required. The following rules are used in the test scenario to relate the inputs to the output.

1) If the ACE / $\text{ACE}_{\text{average}}$ is neg very high OR pos very high, then smartbalancing will be good
2) If the ACE / $\text{ACE}_{\text{average}}$ is neg high OR pos high, then smartbalancing will be average
3) If the ACE / $\text{ACE}_{\text{average}}$ is neg low OR pos low, then smartbalancing will be mediocre
4) If the ACE / $\text{ACE}_{\text{average}}$ is close to zero, then smartbalancing will be poor
5) If the netmargin is poor, smartbalancing will be poor
6) If the netmargin is mediocre, smartbalancing will be mediocre
7) If the netmargin is average, smartbalancing will be average
8) If the netmargin is decent, smartbalancing will be decent
9) If the netmargin is good, smartbalancing will be good

IV. SIMULATION OF TEST SCENARIOS

The suitability of the fuzzy logic is evaluated within different test scenarios. The scenarios consist of assumptions regarding the general market situation the three scenario parameters balancing energy prices, clearing scheme and pricing scheme.

A. Scenario definition

The ACE without market response is 1 GW in all scenarios. All scenarios include three imaginary market participants with 1 GW of technical flexibility each. The marginal costs of these market participants differ with 70, 90 and 110 EUR/MWh.

1) Regarded balancing energy prices: The balancing energy prices vary with the overall market situation. Therefore a favorable and a more expensive MOL are regarded to investigate it's impact on the control. Both MOLs includes 1 GW reserves evenly distributed into 10 bids of 100 MW. The lowest offer is 30 EUR/MWh. The less expensive MOL 1, includes bids up to 120 Euro/MWh, resulting in an initial imbalance price of 75 EUR/MWh with pay-as-bid and 120 EUR/MWh with marginal clearing. Within the more expensive MOL 2 bids rise up to 390 Euro/MWh. The initial imbalance price with pay-as-bid clearing is 210 EUR/MWh and 390 EUR/MWh with marginal clearing.

2) Regarded clearing and pricing schemes: As clearing schemes marginal clearing and pay-as-bid clearing are investigated. For pricing single pricing is compared with combined pricing, as applied in the Netherlands.

B. Results

The results show the effects of the chosen scenario parameters.

1) Results for MOL 1: Fig. 3 illustrates market response with marginal clearing scheme and single imbalance pricing. The imbalance price remains at 120 EUR/MWh for 15 minutes. This leads to an overreaction and a negative ACE of up to - 400 MW. Every 15 minutes there is a drop in price and ACE. After 45 minutes the price settles at 75 /MWh at an ACE of 400 MW. Due to the single imbalance pricing the market participants consider the $\text{ACE}_{\text{average}}$ as risk indicator of a changing sign of the imbalance price, which, in this case can not prevent an overreaction.

With marginal clearing scheme and combined pricing the imbalance price remains at 120 EUR/MWh for 15 minutes, but no overreaction occurs. After 5 minutes the ACE oscillates between zero and less than 200 MW. The market participants consider the ACE as indicator for the risk of a chancing sign of the imbalance price. This avoids an overreaction. With the new imbalance settlement period after 15 minutes, the price collapses from 120 /MWh to just under 40 /MWh, thus reducing the incentive for market participants. The ACE rises to almost 700 MW. With the next imbalance settlement period, the price will settle at 65 /MWh, which corresponds to an ACE of 500 MW. The imbalance could be halved within two periods.

Pay-as-bid clearing results in limited market response of 200 MW at a favorable MOL. The imbalance price decreases and limits market response, since there is no economic flexibility potential as soon as the imbalance price falls under 70 EUR/MWh. There is no difference between single and combined pricing scheme, since the economic potential is zero before the risk of a changing sign of the imbalance price appears.

2) Results for MOL 2: Regarding the more expensive MOL marginal clearing scheme leads to an overreaction and a

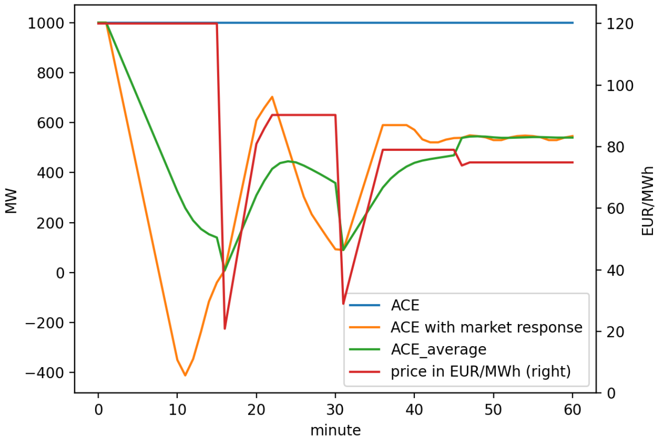

Fig. 3. MOL 1: Marginal clearing, single pricing

negative ACE for both pricing schemes. The ACE reaches -600 MW with single pricing scheme. The overreaction is limited with combined pricing scheme. The imbalance price is set to zero and the ACE returns to 1000 MW.

Fig. 4 illustrates market response with pay-as-bid clearing and single imbalance pricing. An overreaction takes place, but the ACE does not reach - 200 MW. Within 30 minutes the imbalance price drops from 210 EUR/MWh to an almost stable value around 90 EUR/MWh. The imbalance value has a similar pattern starting at 1 GW and stabilizing around 400 MW after 30 minutes.

Fig. 5 illustrates market response with pay-as-bid clearing and combined pricing. No overreaction takes place. The minimum ACE is 100 MW after about 8 minutes. After 15 minutes it stabilizes around 400 MW with a range of about 50 MW. The imbalance price is 90 /MWh.

3) Discussion of the results: With fuzzy logic it is possible to achieve a stable price and ACE state in all presented scenarios. This is reached within a maximum of three imbalance pricing periods (Fig 3). Single pricing causes greater fluctuations in ACE and price than combined pricing. The settling time is also lower with combined pricing with a minimum of 15 min in the case of an expensive MOL at pay-as-bid clearing with combined pricing (Fig 5).

The simulations show that the ACE seems to be a promising input variable in case of combined pricing. It leads to the observed fast and stable approximation to the equilibrium of price and ACE determined by MOL and marginal costs of market participants.

The range of the MOL might be another important parameter to tune the fuzzy logic. In combination with the clearing scheme it influences the incentive. Therefore, both parameters should be considered in fuzzy tuning to avoid overreactions. Limited market responds depends on the marginal costs of market participants and can not be solved by fuzzy tuning.

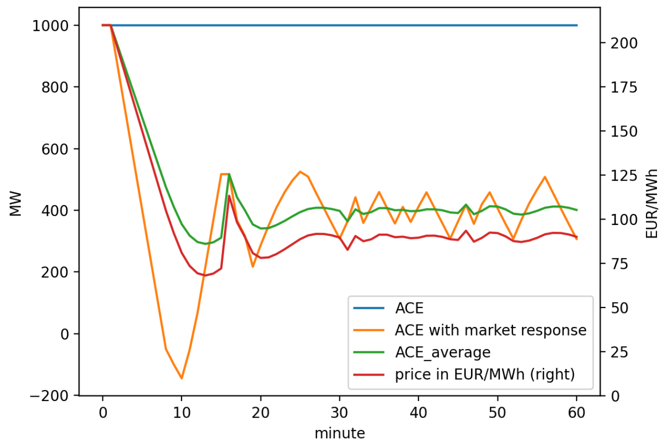

Fig. 4. MOL 2: Pay-as-bid clearing, single pricing

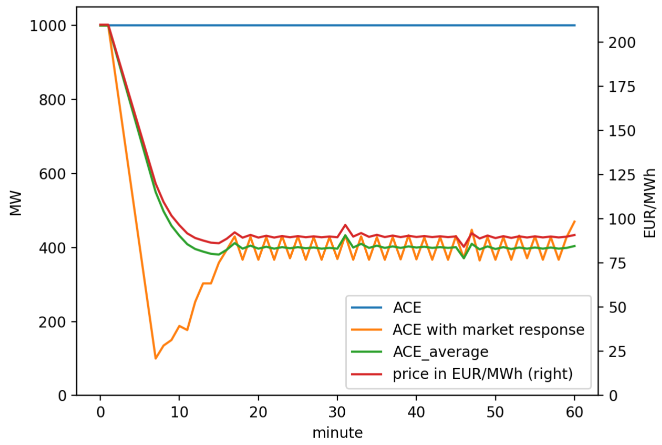

Fig. 5. MOL 2: Pay-as-bid clearing, combined pricing

V. SUMMARY AND OUTLOOK

This study presents fuzzy logic as possible approach for the decision-making process of market participants with regard to the Smart Balancing definition. The imbalance price as existing incentive and the area control error as indicator for the risk of a changing imbalance price are investigated as input parameters. The clearing schemes marginal and pay-as-bid clearing as well as the pricing schemes single and combined pricing were analyzed. Different scenarios consisting of the applied imbalance pricing mechanism, the clearing scheme and the associated MOL are investigated.

The economic flexibility potential and with it the market responds results from the deviation of the control area, the MOL and the marginal cost distribution of the market participants. The scenarios examined show that market response for real-time energy balancing is strongly incentivized by single imbalance pricing. This can lead to overcompensation and requires an additional rule to meet the Smart Balancing definition. The Dutch approach of switching to dual pricing in case of overcompensation, referred to as combined pricing, meets the Smart Balancing definition and prevents unwanted overreactions in three out of four cases. The combination of marginal clearing and high balancing energy bids does lead to an overreaction at combined pricing. The level of the balancing energy bids proved to be a critical safety factor as it determines the financial incentive. A fuzzy tuning adapted to this is to be investigated.

The test scenarios show that a fuzzy logic with the selected input variables can serve to optimize market response for real-time energy balancing. From this first investigations it seems to be a promising tool for grid operators to balance the control area in case of incentivized market response. Future research should focus on identifying the overall flexibility potential and related marginal costs in Germany. A more precise impact assessment on optimal fuzzy tuning and market-design-options can be done with that information.

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