Rule-based Control for Scheduling Electric Vehicle Charging on the Imbalance Market

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***Abstract*-- This paper presents a rule-based control strategy for a flexibility aggregator on the Belgian imbalance market. In this setting the flexibility aggregator can deviate from its day-ahead planning using a set of simple rules, based on historical data of the imbalance price. The strategy is validated on the Belgian electricity market for a flexibility aggregator with a fleet of 1000 electric vehicles for the year 2013. The simulation results show that using a simple rule-based controller, it is possible to reduce the daily electricity cost of the flexibility aggregator with 25%.**

***Index Terms*—Balancing Responsible Party, Demand flexibility, Flexibility aggregator, Imbalance Market, Single Pricing scheme**

I. Introduction

The European Union (EU) has set binding targets to achieve a renewable energy share of 20% in total energy consumption by 2020. EU energy and climate goals have been incorporated into the Europe 2020 Strategy in order to transform to a more competitive, secure and sustainable path [1]. Following the agreement of these targets through the climate and energy package in 2009, most EU member states experienced a significant growth of renewable energy consumption. By the end of 2013, the share of renewables in end consumption already reached 15% [2]. In January 2014, a new and more challenging framework for the period up to 2030 was presented by the European Commission, aiming to make the EU's economy and energy system more competitive, sustainable and secure [3].

Notwithstanding these political goals, most electricity produced by Renewable Energy Sources (RES-e) is variable and difficult to predict, by nature. The ever increasing volume of RES-e challenges current power system operations, where maintaining the balance between generation and consumption presents an important integration problem [4]. Different studies have shown that due to a higher input of RES-e during the last years, system imbalances and thus imbalance costs have amplified [4,5]. Moreover, factors such as limited storability and a variable consumption increase uncertainty for bidding strategies on forward electricity markets.

To match production and consumption of electricity, a certain level of adaptability and flexibility is required. Demand response can contribute to system stability and thus encourage a higher share of RES-e. Demand Side Management (DSM) refers to the shaping of the electrical grid to improve the fit with the supply side. A first way to do this is by confronting the end user with a dynamic financial incentive to influence his demand [6]. The Smart Grid concept enables coordination between production and consumption.

In this paper, we address the balancing problem by assessing the flexibility of an electric vehicle (EV) park managed by an EV aggregator. The scenario is deemed highly relevant for a more sustainable and less oil-dependent mobility infrastructure of the future. The demand flexibility of EVs can contribute both to system stability and to increase utilization of renewable electricity for vehicle charging [7].

In the remainder of this paper, the current situation on the Belgian balancing market will be analyzed in Section 2 after which the specific balancing problem for an EV aggregator is described in Section 3. In Section 4 two balancing strategies for the EV aggregator are described and analyzed. Finally, conclusions are formulated in Section 5.

II. Balancing on the Belgian electricity market

In order to ensure grid stability, a balance between the demand and supply of electricity must be remained at all time. This responsibility is in Belgium, like in other countries, transferred from the Transmission System Operator (TSO) to the Balancing Responsible Party (BRP). The BRP can be an electricity producer, a major consumer, an electricity supplier or a trader. This section describes different aspects for short term balancing on the Belgian electricity market. Actual Belgian day-ahead market prices and imbalance prices from the year 2013 were used for the subsequent analyses.

A. *Belgian Spot Market*

Participants on electricity spot markets schedule generation and demand for the next day (day-ahead) or current day (intraday). The price on these markets is formed by the general principle of demand and supply, resulting in a settlement price that is based on the marginal bidding price [8]. Demand of electricity changes significantly during the day, but can be predicted fairly well over the day. Variations on the supply of electricity are mainly influenced by the feed in of renewable and the availability of conventional power plants. In this paper, we focus only on the day-ahead market, since the traded volumes and liquidity are much higher than on the intraday market [9]. The Belgian power exchange day-ahead market, the Belpex[1], is coupled with the APX in the Netherlands and the EPEX Spot in France and Germany. These spot markets close at 12:00 of the preceding day, i.e. this is when trading for hourly contracts for the 24 hours of the coming day is closed. Prices are negotiated for every single hour. In this way, a connected price time series can be generated that can help in predicting an optimal load curve for optimal flexible consumption.

B. Provision of Balancing Services

The TSO is the final responsible for maintaining the equilibrium between electricity production and consumption at all time. In order to fulfill this task, the TSO has BRPs at every grid access point. The BRP is responsible for forecasting, scheduling and balancing their injections and off takes. Unpredicted real-time fluctuations require balancing services, contracted by the TSO. These are most of the time large generators or consumers who will adjust their production or load accordingly.

The relation between the spot and balancing market is shown in Figure 1. If an imbalance occurs between take-offs and injections, the TSO will apply an imbalance tariff to the BRP, corresponding to the amount of necessary reserve energy.

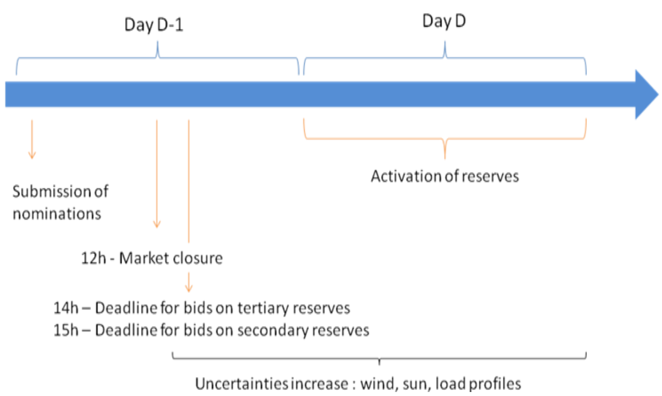

Figure 1: Time lapse of different aspects of balancing management in Belgium

C. Allocation of Energy Payments

Internationally a difference exists between single and double pricing schemes for imbalance tariffs. Under a single imbalance pricing scheme, also referred to as one-price system in literature [10], imbalance prices represent the marginal procurement price of balancing services, i.e. either upward or downward regulating services depending on the overall status of the system. The same imbalance tariff is applied for remaining short and long positions, making it in theory a non-profitable case for the TSO. In contrast, in a dual pricing system, a different pricing scheme is used for positive and negative imbalances. While imbalances that contribute to the system imbalance are priced the average of the procurement of imbalance services, BRPs with a position that counter the system imbalance are priced on basis of wholesale energy prices. Compared with the single pricing scheme, the latter can avoid speculating on the direction of the system imbalance, for example creating a short position when the system imbalance is long and vice versa [10]. However, since it is unlikely for generators to speculate on the basis of short term settlement periods, a market with a single pricing scheme is preferred by aggregators with a flexible load in their portfolio as will be discussed in this paper, since this pricing scheme allows them to generate real time profits in case they counter the system imbalance by taking a position in their own portfolio.

[1] Every market participant is connected to a BRP in Belgium that balances its positions for every 15 minutes for all its access points. In this way, it will minimize deviations between these nominated positions and real-time. Nominations have to be sent to Elia before a fixed gate closure. This includes expected injections and off-takes at access points, nominations for power exchanges between BRPs and import and export nominations at the border of the control area [5].

III. Scheduling of Electric Vehicle charging

With the International Energy Agency expecting a mass adaption of EVs in the next decades [11], the increase in the demand for electricity will be significant if charging is uncontrolled. It is necessary to see the effects of controllability in a pool-based market set up, such as the Belpex. In such a set up, the charging schedule of the EVs will have to be submitted by an aggregator to the market. In order to quantify the impact of EV charging on the future electrical system, it is essential to understand the typical behavior of electric car users, i.e. their driving patterns and driving times. This input to the modeling of the EVs in this paper is based on the research carried out by Van Roy and Leemput [12].

A. Flexibility profile

Each EV has a demand of energy that has to be fulfilled before a certain time e_{end} , for example the moment when the EV user leaves for home when he charges his car at a parking lot at work. It is considered that the maximum charging capacity cannot be negative, i.e. on the moments that an EV is not charging, he will not discharge either.

The flexibility of the EVs permits the aggregator to charge on the most beneficial moments. Naturally, this flexibility itself has its own constraints. The maximum and minimum, in between which the charging profile has to stay, will be called the flexibility profile. The lower boundary of the flexibility profile is formed by e_{min} and is found by delaying charging that much until the moment is reached where the battery will have to charge at full capacity in order to reach e_{end} before the end of the day. e_{max} on the other hand is calculated by starting to charge directly at full capacity until e_{end} is reached.

The aggregator tries to optimize the aggregated model by making use of a dispatch algorithm that divides the energy between all the vehicles. Both for the aggregator himself, i.e. the entity that nominates on the electricity markets on behalf of the owners of the EVs, as for the grid operator this is a more interesting approach. For both players total demand of power, reduction of imbalances and preventing congestion of the net are of importance.

The flexibility profile was constructed simulating realistic data of the charging profiles of 1000 EVs. More information on how this profile was formed can be found in [12]. In short, different categories of EVs for different usage purposes are analyzed where the duration of the trips for each of these categories can vary accordingly. Moreover it is assumed that not all cars will charge for a full battery, and that not all cars will have as much time to charge as others. Figure 2 depicts the flexibility profile in which the charging profile of the aggregator has to stay. The assumption is made in the rest of this paper that the flexibility profile for each day is the same and perfectly predictable.

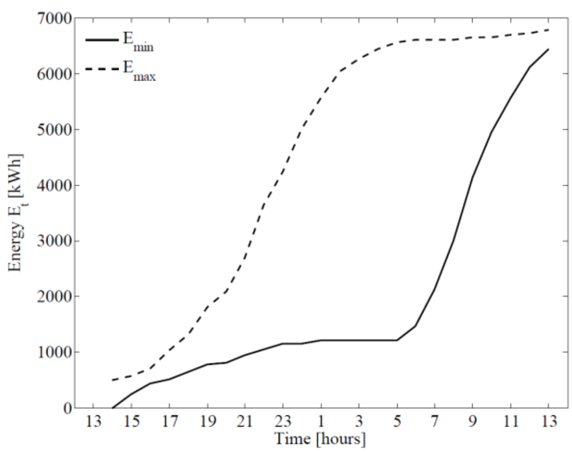

Figure 2: Flexibility profile for charging a fleet of 1000 electric vehicles. The first EVs arrive at 2 pm and the last leave at noon of the following day. Total demand is 7MWh. E_{min} and E_{max} define the flexibility profile of the aggregator.

B. *Nested optimization problem*

The exact moment at which the EV is charged is most of the time not important to the driver, he is only interested that the car has a full battery when he wants to leave again. Because of the long periods during which a car can be charged, the moment of charging can be moved according specific grid stabilizing needs. Therefore charging a fleet of electric vehicles as a flexible load can be used to provide services that counter system imbalances [12]. In the described model, the power will be distributed under the individual EVs using a dispatch algorithm. The advantage of going by a dispatcher is that it becomes possible for the aggregator to work with only one aggregated power.

The aggregator of the EV fleet would like to see the charging costs minimized over the day. In order to do this, he should utilize the flexibility in his portfolio on the most profitable moments during the day. Since the cost is subject to different uncertainties on the electricity markets, the user will be interested to minimize the expected value of the total cost. This cost depends on two different components, namely the cost on the day-ahead market and the costs made in real time on the imbalance market. The objective will be to decide on the bidding strategy that will minimize this total cost.

The total cost minimization function of the aggregator is described in (1). With respectively λ_{DA}, λ_+ and λ_- the price on the day-ahead market and imbalance tariffs on the positive and negative imbalance market. P_{DA} and P_{RT} are the power nominations made on the day-ahead market and the real time power profile.

$$f = \underset{P_{DA},P_{RT}}{\text{minimize}} \underset{\lambda_{DA},\lambda_+,\lambda_-}{\mathbb{E}} \left\{ P_{DA} \cdot \lambda_{DA} + \underset{P_{RT}}{\text{minimize}} \underset{\lambda_+,\lambda_-}{\mathbb{E}} \{\Delta p^+ \cdot \lambda_+ + \Delta p^- \cdot \lambda_-\} \right\} \quad (1)$$

With

$$\Delta p^+ = max(P_{RT} - P_{DA}, 0) \quad (2)$$

$$\Delta p^- = max(P_{DA} - P_{RT}, 0) \quad (3)$$

The nested optimization problem in (1) is subject to a large number of stochastic variables. This problem suffers under the curse of dimensionality, stating that the cost of computing players' expectations over all possible future states increases exponentially in the number of state variables. In the strategies discussed next, certain assumptions are made in order to simplify this problem.

IV. STRAGTEGIES AND RESULTS

Using historical generation profiles and current EV characteristics, we model an EV park, consisting of 1000 vehicles with a battery capacity of 10KWh. The power will be distributed under the individual EVs by using a dispatch algorithm. The aggregator has to satisfy electricity demand for the EV and thus can only charge during a certain time during the day, during which the cars have to be become fully charged at a minimal cost. In the described strategies, a simplification of the nested optimization problem (1) entails a split up of both minimizations. First, the aggregator will try to optimize his load profiles to the day-ahead market price. He will place bids on the day-ahead market to his best prediction, resulting in the first term in (1). If intraday large imbalance tariffs are observed, an additional objective of the aggregator, is to employ the flexibility of the EV in such way that the demand is corresponding to the imbalance tariffs. These are expected to result in a negative cost for the last two terms in (1). In this way, the aggregator will contribute to power system stability and minimize his own charging costs.

A. *Rule based controller*

It is assumed that the EV user gives the aggregator the necessary information about the requested energy and the departure time. This is necessary because all batteries of the EVs have a certain maximum charging capacity rate and hence need a certain time to charge. This paper discusses the case where the cars charge at a parking lot and thus charge during the day, for example at public parking lots or at the office.

A fixed work shift is assigned to each vehicle. It is an acceptable approximation to say that all vehicles have a fixed departure and arrival time since 82% of the population has fixed working hours [12]. To create some variation between the different vehicles, a uniform probability distribution function is used to determine the exact minute of departure and arrival. For more information on the discussed behavior of the EV owner, see [12]. In this way the limits of the charging regime can be decided, as is shown in Figure 3 by the outer lines. The bids of the aggregator on the day-ahead market P_{DA} and the real time charging adjustments P_{RT} will always have to stay between these limits. In Figure 3 the day-ahead nominations are shown by the solid line, while real time energy demand is visualized by the dashed line in the upper subfigure. The day-ahead (solid line) and imbalance price (dashed line) are depicted in the lower subfigure.

Making intraday a prediction of the imbalance price, the aggregator can adjust according to the difference of the imbalance price and the average based on historical data. When the price is above the average, than it is preferred to go short, i.e. consume more energy temporarily and preferably sell it later on again for a higher price. In principle, it would be possible to discharge the cars when imbalances prices are very high. For our model, we assumed the EV do not charge nor discharge when imbalance prices are high. As can be seen in Figure 3, in this way the real time profile follows the quarter-hourly imbalance tariff.

The strategies make use of a simple intraday prediction method for the imbalance price. The prediction of the imbalance price is compared with the average imbalance price λ_{mean}, taken over a period varying from the preceding year to the preceding day. The best period for 2012 was seen to be the two preceding weeks, which is validated for the best strategy for 2013. The prediction of the imbalance price is compared with the average imbalance price over the whole duration of the preceding year. A threshold of 10% is added to this technique in order to only act in real time when imbalances are large. The rule-based controller ensures the real time power profile is described by (4).

$$P_{RT} = \begin{cases} P_{max}, & \text{if } \hat{\lambda}_{RT} \leq 0.9 \cdot \lambda_{mean} \\ 0, & \text{if } \hat{\lambda}_{RT} \geq 1.1 \cdot \lambda_{mean} \end{cases} \tag{4}$$

1. Strategy 1

The first strategy is characterized by a constant load profile. The day-ahead nomination of the aggregator therefore only depends on the total amount of cars and their capacity. One advantage of this model is that there is much room for regulation intraday, i.e. the limits of the charging area will not be reached quickly.

2. Strategy 2

For the second strategy, we assume that a perfect prediction of the day-ahead market prices can be made. When day-ahead prices are perfectly known, the aggregator will optimize his day-ahead nomination. The limits of the charging area will however be reached more quickly, when intraday adjustments are made compared with strategy 1.

Both strategies are visualized for a sunny day in the Summer of 2013 in Figure 3. As can be seen P_{DA} follows the constant profile as expected during the day for strategy 1. For strategy 2, day-ahead nominations are optimized according to the day-ahead profile. P_{RT} shows how this course is adjusted during the day by reacting on imbalance tariffs. Since the real time strategy of both strategies is the same, P_{RT} follows the same profile in both strategies. On the moments where the imbalance tariff peaks, the real time strategy will be to avoid charging.

3. Perfect knowledge

In order to benchmark these results, a suboptimal case will first optimize day-ahead nominations according to day-ahead prices. In a next step, an extra real time optimization according to the imbalance prices will take place. Therefore the results found in this section are a good way to benchmark the results of the earlier discussed strategies, since in all strategies the day-ahead and real time profiles were considered independent as well. Perfect knowledge of imbalance tariffs would raise profits for the EV aggregator on the imbalance market by a factor 10. Imbalance tariffs are hard to predict by nature, showing that strategy 2 already gives interesting results.

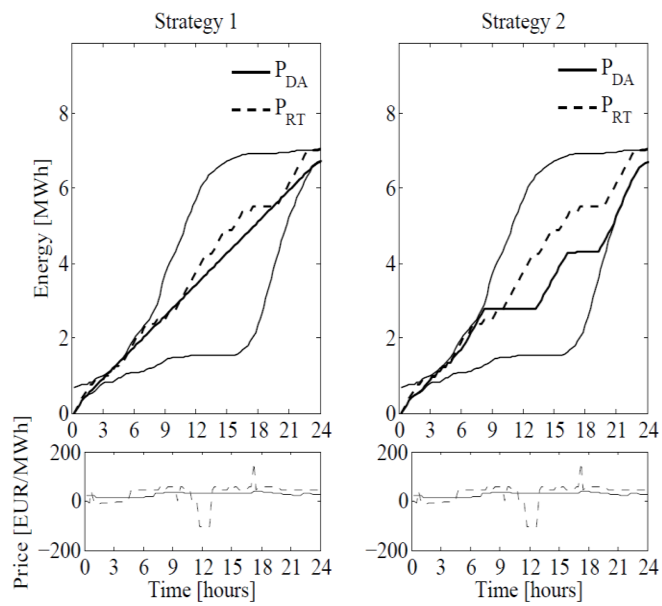

Figure 3: Constant charging strategy (left) and Day-ahead optimized charging strategy (right), 15/01/2013

B. *Results*

Results for both strategies and the benchmark for an EV aggregator acting on the Belgian electricity market in year 2013 can be found in Table 1. The results are given on a daily average basis.

As expected, the first strategy, describing a constant load profile, will have a higher day-ahead cost since it does not optimize its day-ahead bids according to day-ahead market prices. However, since this profile gives more room for adjusting intraday according to imbalance prices, the profit made by the aggregator selling his extra capacity on the imbalance market will be more significant. We can see that using strategy 2 (optimize according to day-ahead prices), the day-ahead cost of €288,34 can be lowered by €26,35, or 9%. These results can be found as well in Figure 4. One can see that the day-ahead price will make a shift to the right, giving a more centered solution for strategy 1.

As was mentioned above, a period of two weeks ahead was the best to calculate λ_{mean} for 2012. The results when this period is validated for 2013 can be found in Table 1.

Imbalance profits increase significantly in this way and can lower the normal day-ahead cost by 25%.

TABLE I
Daily Average Charging Cost by Strategy

Strategy $\lambda_{\text{mean period}}$	**Strat. 1 yearly**	**Strat. 2 yearly**	**Strat. 2 2 weekly**	**Perfect Knowledge**
Day-ahead market	-318,03	-288,34	-288,34	-288,34
Imbalance market	42,76	26,35	71,92	212,10
Total	-275,28	-261,97	-216,42	-76,24

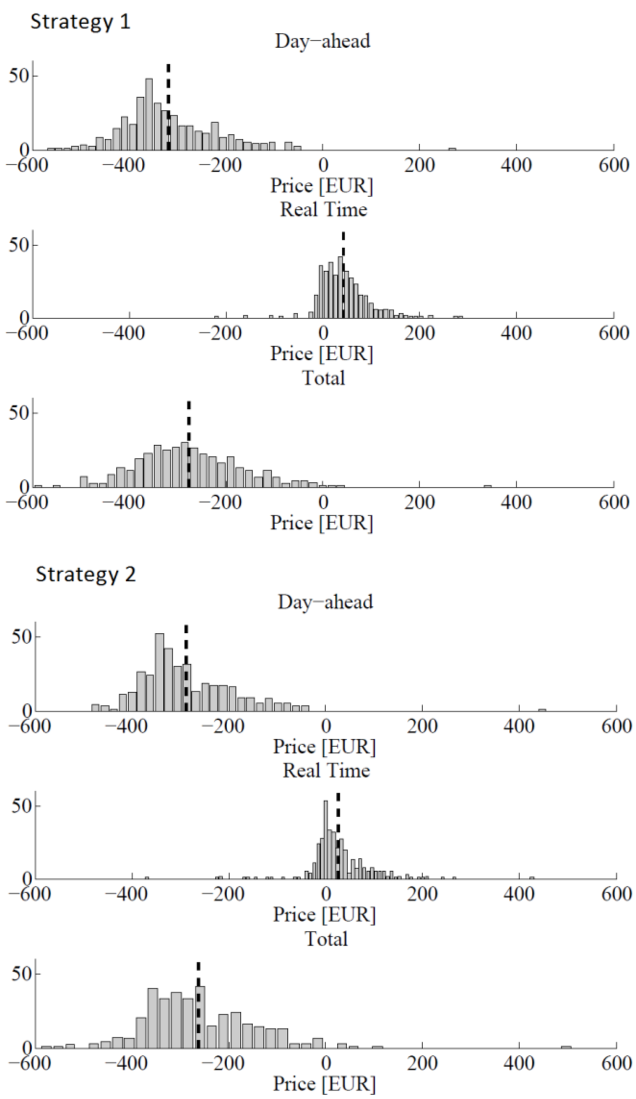

Figure 4: Daily average charging costs for strategy 1 (up) and strategy 2 (down), mean shown by dashed line. Strategy 1, which has a constant day-ahead nomination, performs worse on DAM, leading however to more room in real time to make adjustments. Strategy 2 making its nominations on DAM according to DAM price variations, performs better in total.

V. Conclusions

In this paper we used a rule-based controller based on the average imbalance price. We examined a case study, where an aggregator has 1000 electric vehicles with a capacity of 10kWh in his portfolio. Using the flexibility in his portfolio, we tested two different strategies on the basis of price data of 2013. Both strategies used the same set of rules on the imbalance market. The first strategy scheduled a constant load profile day-ahead where the second strategy optimized its day-ahead nominations according to day-ahead prices. This second strategy resulted in a total charging cost reduction for the EV aggregator of 25%. Benchmarking the results to the case of perfect knowledge of both day-ahead market price and imbalance tariffs showed that the profits on the imbalance market of the rule based controller achieve 34% of this optimal model. In our current implementation the threshold is based on historical data, optimizing the rules for setting this threshold should improve the rule-based controller.

VI. Acknowledgment

The authors would like to thank all colleagues, especially Juan Van Roy for providing the availability and consumption profiles of electric vehicles.

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