Increasing power system reserve capacities by changing the reserve market design: the case of Electric Vehicle fleets

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***Abstract*—Variable Resource Renewable Energy (VRRE) penetration has grown rapidly in recent years, creating a need for additional reserve power supplies. Distributed Energy Resources (DERs) have also been identified as reserve power providers, if market rules are favorably modified for these new units. This paper aims to show that the ability of DERs to provide reserve power is dependent on the market design considered, by focusing on primary frequency control and unidirectional Electric Vehicles (EVs). A simulation model is built for an EV fleet taking account of user behaviors. Simulations are conducted considering two market designs: symmetrical (where upward and downward reserves are procured jointly) and asymmetrical (where they are procured separately). In the asymmetrical configuration, the EV fleet performance is also compared on the basis of 1h and 4h market clearing periods. Results show that the EV fleet provides on average nine times as much power under an asymmetrical framework as under a symmetrical one. Similarly, reducing the product duration from 4h to 1h enables the EV fleet to provide more than two times as much reserve power. System operators could implement these favorable market rules for DERs, as it could maximize the provision of reserve power supplies by DERs.**

***Index Terms*—Electric Vehicles; Power System Reserves; Market Design; Distributed Energy Resources**

I. Introduction

THE penetration of Variable Resource Renewable Energy (VRRE), such as wind mills and photovoltaic (PV) solar panels, has rapidly increased in the past few years and this trend is expected to continue as many governments committed themselves to further developing VRRE within the framework of the COP21 agreement. The International Energy Agency forecasts that renewables will satisfy 50% of electricity needs in Europe by 2040, around 30% in China and Japan, and above 25% in the USA and in India [1]. In the literature, a number of papers convincingly argue that the electric system could be powered 90% to 99% of the time entirely from renewable power sources, at costs comparable to today's but only if the mix of generation and storage technologies is optimized [2].

VRRE have very low marginal costs and are CO_2 emission free. The growth in global electricity demand has been decelerating in OECD countries and in China in recent years [3]; in this context, the increase in the share of VRRE production has led to a decrease in bulk electricity prices. Consequently, conventional electricity generation technologies are finding it increasingly difficult to compete: first, as coal plants are rather inflexible and release large quantities of CO_2 (1000 g CO_2/kWh), the share of coal in the energy mix is expected to drop significantly [1]; the operating hours of gas power plants have been drastically reduced in recent years, making it difficult for them to cover their costs [4], [5]. Even if they are well suited to balance RES variability, gas power plants will need to increase their flexibility with high ramping capacities and the design of the gas market should also be adapted [4].

VRRE are intermittent by nature. Even if progress has been made in this area, they are still less predictable than other power sources and reduce the natural inertia of power systems. Increasing the share of VRRE could lead to power system imbalances and jeopardize grid stability [6], [7]. On the other hand, power systems will have less short-term flexibility as fast-ramping power plants (gas) may be shut down if their costs are not covered. This situation is a new challenge for System Operators (SO) responsible for reserve power management to deal with all types of system imbalances. With increasing VRRE penetration and the closure of conventional power plants, reserve needs and associated costs will increase in the future [8]. Reference [9] illustrates this phenomenon for various regions in the world.

Distributed Energy Resources (DERs), such as controllable loads, micro-CHP units or Electric Vehicles (EVs), could act as additional flexible and cost-effective reserve providers and could replace traditional power plants in SO' reserves [10]. By doing so, they would help to provide the reserve resources needed and potentially to increase the share of VRRE that can safely be integrated in the system. However, the different types of SO' market designs, initially intended for conventional power plants, have to evolve to enable the integration of DERs in SO' reserves, at the both distribution [11] and transmission levels [12], [13].

The aim of this paper is to show that DERs could significantly improve their participation in reserve markets thanks to the adaptation of SO market designs. To achieve this objective, the paper focuses on primary frequency control market – owing to its identification as one of the most promising grid services for DERs [10] – and on Electric Vehicles (EV) – as their ability to provide such reserves has already been demonstrated [14], [15], and as they are enjoying rapidly increasing penetration worldwide [16]. Different market de-

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signs are considered and the performance of an EV fleet providing primary frequency control is appraised for these different market designs and comparisons are made between them. A dynamic, stochastic simulation model is developed for the purpose of quantitative analysis.

In order to provide the SO with a service of this type, EVs need to be clustered in EV coalitions under the supervision of an aggregator [17], [18] responsible for: (a) presenting the EV fleet as a single entity to the SO; (b) forecasting future EV conditions and the corresponding fleet availability for reserve markets; and (c) measuring the frequency and distributing the reserve power among the EVs in real time according to the frequency deviations.

The possibility of having an EV fleet participate in the frequency control mechanism has already been proposed and the expected revenues have been calculated [19], while EV fleet controls have been proposed in previous works by [20], [21]. EVs are either assumed to have bidirectional (V2G) or unidirectional capabilities (charging mode) only. The design of the frequency control market is extremely important [13]; in particular, the aforementioned surveys usually consider an hourly symmetrical market[1]. In such a market, the EV fleet has to bid the exact same amount of upward and downward reserve power for each hour. EVs with unidirectional capabilities perform very poorly a such market design of this kind, because they have to charge constantly at low power in order to provide symmetrical reserve power around their charging power [23], [24].

However asymmetrical markets, i.e. markets that are divided into two independent sub-markets (one dedicated to the trading of upward products, and the other to the trading of downward products), already exist in some countries (e.g. Denmark [25]) and they are likely to further develop in the near future as the ENTSO-E recommends this type of market design in the grid codes [26].

Similarly, the market clearing period is one hour in some regions (e.g. in PJM [27]), but it may be higher in others (e.g. four hours in Denmark [25], one week in Germany).

This paper assesses the possibility for an EV fleet with unidirectional capabilities to participate in a market dedicated to the provision of DOWN products only. The fleet performance under such a market design is compared with the performance of the same fleet operating in a symmetrical market. The impacts of having different market clearing periods of 1 hour and 4 hours are also evaluated.

The main contribution of this paper is to provide a quantitative assessment of the impacts of different frequency control market designs on the ability of an EV fleet to provide frequency control reserve power. The method and algorithms employed in this work are tools used for a more general purpose.

The paper is organized as follows. Section II provides a description of the data used along with a presentation of the simulation model and its operating principle. In section III, the simulation results are presented and discussed. A conclusion to the article is included in section V.

[1]Reference [22] identified reserve transaction mechanisms other than markets such as bilateral contracts. However, such regulated conditions are not ideal for new DERs [13].

II. Modeling

A dynamic, stochastic simulation model is built taking account of EV users' driving patterns and behaviors. An aggregator is responsible for controlling the charging power of the EV fleet to provide frequency control products through a market dedicated to the trading of downward products. The role of the aggregator is specified in Figure 3 of reference [13]: each EV i connected to a plug communicates its reserve power P_{bid_i} to the aggregator who can offer the power P_{bid} in the frequency reserve market.

According to the classification provided in reference [28], which reviews the existing smart charging approaches in the literature, we implement a decentralized algorithm considering unidirectional capabilities for frequency control purposes based on a multi-agent system strategy using Matlab[2]. Each EV represents an individual agent, which decides by itself the amount of reserve power it can provide to the aggregator (see section II-C3). The aggregator is then responsible for bidding in the frequency control market and for distributing the reserve power in real time among the EVs based on their individual decisions.

First, the EV fleet's characteristics are defined in section II-A. Then, the EV usages for transportation are modeled in section II-B. Section II-C presents strategies of the aggregator and EVs for participating in the frequency control market. Finally, section II-D features the characteristics of the frequency data set.

A. EV fleet characteristics

For the sake of simplicity, all the vehicles are assumed to be full-electric vehicles (EVs) and to have a maximum battery capacity (C_{max}) of 22kWh like more than 60% of the EVs sold in France in 2015 [30]. The constraint $0.2 < C/C_{max} < 0.9$ is added, with C representing the present battery capacity, in order to avoid reaching extreme SOC values, which could severely damage the battery [31].

The power level of the charging stations, the so-called Electric Vehicle Supply Equipment (EVSE), is based on current French values [32]. Table I presents the charging level distribution for both home and work EVSEs. All EV owners are assumed to have the ability to charge at home and at work[3].

B. EV trip patterns

Electric Vehicles (EVs), will primarily be used for transportation purposes. The EV driving patterns will then determine the ability of these vehicles to be used as distributed energy storage units within the framework of an electric grid reserve. Data from the French ministerial National Transport and Travel Survey (ENTD) was used to characterize the

[2]Decentralized algorithms are scalable and require less communication means. On the other side, centralized algorithms perform slightly better in providing reserve [29].

[3]A sensitivity analysis on the EVSE penetration level at work has already been carried out in a previous work [23].

TABLE I
BREAKDOWN OF HOME AND WORKPLACE ELECTRIC VEHICLE SUPPLY EQUIPMENT (EVSE) BY CHARGING POWER LEVELS

Charging level	*Home EVSE*	*Workplace EVSE*
Slow charging A (3kW)	95%	35%
Slow charging B (7kW)	5%	34%
Intermediate charging (22kW)	0%	29%
Fast charging (43kW)	0%	2%

potential EV fleet's driving patterns and to identify the values of trip-related data. This survey provides information about the mobility patterns of a representative sample of French residents. All the data derived from this survey are made publicly available [33].

In the ENTD survey, each respondent reported their mobility patterns for weekdays and weekends, providing detailed information about their trip durations, distances, transportation modes, departure and arrival times for all trips. The initial database is very large and covers many different types of mobility patterns; it comprises 35,803 car trips made by 9,630 drivers.

For the sake of simplicity, only commuting trips were considered in this analysis because of their representative nature, considering that they account for most of the trips and kilometers driven (for instance in France [34]), which makes the results a good initial basis for estimation. Similarly, only drivers who drove less than 100km per day were considered, because other drivers' car usages are not consistent with today's EV driving ranges.

After having processed the initial data set accordingly, key parameters of work-related mobility patterns were deduced: means and standard deviations for trip distances, durations and departure and arrival times are summed up in table II. The energy consumption while driving is extracted from CROME demonstration project results [35]; $c = 156.5Wh/km$ is used.

TABLE II
EV TRIP PATTERN CHARACTERISTICS, DEDUCED FROM ENTD SURVEY

Variable	*Notation*	*Min*	*Max*	*Mean*	*Median*	*Std*
Distance (km)	l	1	99	36	32	23
Duration (min)	d	18	1530	59	54	34
Departure time	t_d	04:00	18:20	08:13	07:50	127min[a]
Return time	t_r	03:35	23:59	17:49	18:15	171min[a]

[a]Values provided in minutes

The values from table II are used to build a dynamic, stochastic EV fleet model; each EV has its own trip characteristics, which differ from one day to the next. Departure and return times, distances and durations follow Gaussian laws whose parameters are set according to table II.

These values have an impact on the EV availability for grid reserve purposes as they directly impact the minimum State-of-Charge (SOC_{min}) allowed at each moment, which not only

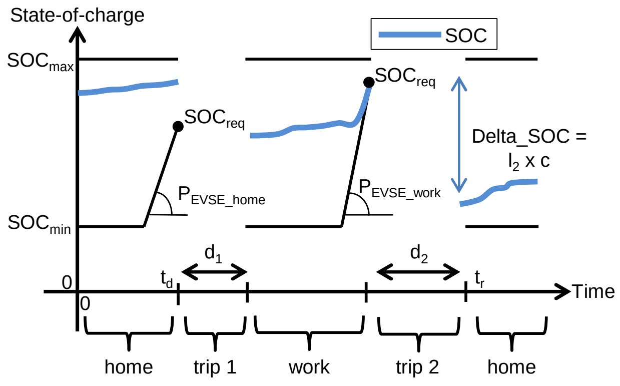


Fig. 1. Typical daily trip patterns for an EV, and the associated upper and lower SOC allowed. Trip notations refer to table II. For illustrative purposes only.

depends on the battery characteristics but also on the future needs for transportation and on the available EVSE power level. A typical daily SOC pattern is illustrated in figure 1 with the upper and lower SOC limitations (respectively SOC_{max} and SOC_{min}) and the different parameters from table II.

In addition, in order to account for the users' range anxiety, the assumption described in equation (1) is made:

$$\forall i \in 1..N_{EV}, \forall j \in 1..N_{trip_i}, SOC_{req_{i,j}} = c \times \max_j d_{i,j} \quad (1)$$

with N_{EV} the number of EVs, N_{trip_i} the number of trips for the i^{th} EV, $SOC_{req_{i,j}}$ the required SOC for the j^{th} trip of the i^{th} EV and $d_{i,j}$ the distance of the j^{th} trip of the i^{th} EV. This means that drivers estimate all their future trip requirements as those of their longest trip in the simulation.

C. Modeling of the participation in the DOWN primary frequency control market

1) Market Design Framework: The grid frequency always fluctuates around its nominal value (50Hz in Europe, 60Hz in the US and in Japan for instance), following the deviations between production and demand. Surplus production results in a frequency increase, and vice versa. Transmission System Operators (TSOs) are responsible for maintaining the frequency within a given range on a continuous basis. In order to do so, they usually implement three control mechanisms (primary, secondary and tertiary)[4].

The present paper focuses on the contribution of electric vehicles to the primary frequency control. This control is an automatic system. At present, this reserve power is mainly delivered by large power plants. The power system frequency is measured with a short sampling rate (<1s) and generators have to react accordingly by changing their operating power. UP products are aimed to increase the frequency (they then represent either an increase in generation power, or a decrease in power demand) and, in contrast, DOWN products are used to reduce the frequency.

[4]More information about frequency control mechanisms is available in [36], [37].

Reference [13] already showed that there is a wide diversity of frequency control market rules among the TSOs. In the present paper, the primary reserve procurement method is assumed to be an auction with a given market clearing period. Thus an aggregator representing the EV fleet is responsible for bidding in the market in advance and for distributing the requested reserve power among the vehicles in real time.

The aim of the present paper is to test different market designs in order to assess the impacts on the ability of an EV fleet to participate in this control mechanism. More precisely, a comparison is made between a *symmetrical* market, i.e. a market in which DOWN and UP products are procured jointly, and an *asymmetrical* one in which there are two separate markets for each kind of product. Within a *symmetrical* market, the same amount of UP and DOWN reserve power has to be bid in each market clearing period. The other objective is to evaluate the impacts of having a longer market clearing period: one-hour and four-hour market clearing periods are compared.

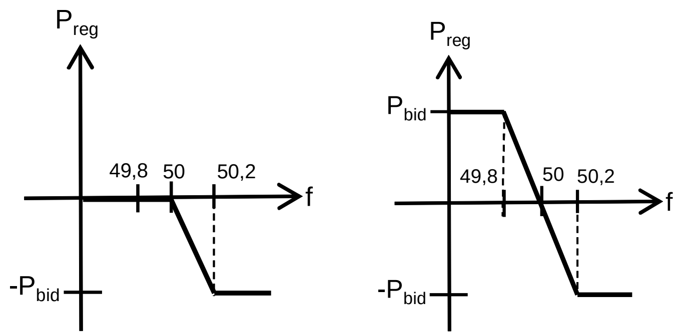
Although economics are out of the scope of this paper, the EV fleet is considered to be a relatively small market player compared to the traditional competitors. Consequently, the fleet is assumed to be a *price taker* having no impact on the market clearing process.

Two algorithms are therefore required : a *scheduling* algorithm (section II-C-3) that will assess the potential offers that can be made in the market in the future based on the expected EV conditions; and a *dispatching* algorithm (section II-C-2) that distributes the power among the EVs in real time. Here, the emphasis is laid on the real time behavior of the EV fleet, and how the dispatching algorithm operates to control the fleet. Thus, the results presented should be perceived as an upper limit of the amount of power that can be provided by the EV fleet at each moment; it could then be used to design appropriate scheduling algorithms.

In the rest of the section, the *dispatching* algorithm operating principle is specified both for the *symmetrical* and *asymmetrical* frameworks.

2) Aggregator dispatch algorithm: Whether operating in a symmetrical or in an asymmetrical market, the operating principle of the dispatching algorithm is the same. At each market clearing period, each EV i provides the aggregator with its available power for frequency control P_{bid_i} until the next clearing period (see section II-C3 for the P_{bid_i} calculation method). The aggregator, by summing up all the individual EV contributions, can thus deduce the total fleet power available for frequency control P_{bid} until the next clearing period. Then, within this period, the aggregator measures the frequency at each time stamp (1s). Depending on the frequency value, it computes the power for frequency control that should be provided to the TSO P_{reg} according to figure 2, where figures (2a) and (2b) respectively represent P-f curves under asymmetrical and symmetrical frameworks. In these figures, positive power stands for an increase in the charging rate and vice versa. These figures reflect the required response of primary reserve units to frequency deviations [38].

Finally, the aggregator sends requests to the available EVs in order to actually provide the TSO with the requested frequency control power, by first requesting charging power from the EVs that have the lowest State-of-Charge (SOC) compared to their future energy needs for transportation.



(a) Asymmetrical framework (b) Symmetrical framework

Fig. 2. EV fleet power response to frequency deviations (negative power stands for an increase in charging rate and vice versa)

3) Individual EV power for primary frequency control: The available power of each EV for frequency control is computed at the beginning of each market clearing period. The calculation method makes a distinction between the asymmetrical and symmetrical cases.

a) Symmetrical Market design: in this market design, each EV has to provide the same amount of UP and DOWN primary reserve power. As only unidirectional capabilities are considered (charging only), EVs need to charge at a setpoint – which will be called the preferred operating point (POP) – in order to be able to modulate their charging power in upward and downward directions around this setpoint. The POP is computed at each market clearing period as the power that would allow the EV to reach its required energy for transportation for its next departure:

$$POP_i = \max\left(\min\left(\frac{SOC_{req_i} - SOC_i(t)}{\Delta t}, 0\right), P_{EVSE_i}\right) \tag{2}$$

with SOC_{req_i} the required energy of the ith EV for its next trip, $SOC_i(t)$ the current state of charge of the ith EV, P_{EVSE_i} the EVSE power capacity and Δt the time before next departure. It is worth noting that negative power stands for charging paper throughout this paper, and vice versa (generator sign convention). The available individual power for primary control is then simply calculated using the equation (3):

$$P_{bid_i} = \min\left(|POP_i|, |P_{EVSE_i} - POP_i|\right), \tag{3}$$

with P_{bid_i} the individual available power for primary frequency control of the EV i. Let us consider the following numerical example: if Δt = 8h, SOC_{req_i} = 0.9 and $SOC_i(t=0)$ = 0.5 then POP_i = 0.4*22kWh/8h=1.1 kW and P_{bid_i} = 1.1 kW during 8h.

b) Asymmetrical Market design for DOWN reserve: Figure 3 shows the different use cases for the EV decision process in an asymmetrical market, for a time slot during which the EV is plugged-in (related to figure 1)[5]. The thick

[5]The different situations depicted in figure 1 are not necessarily sequential in this order; this will depend on the SOC evolutions of each EV.

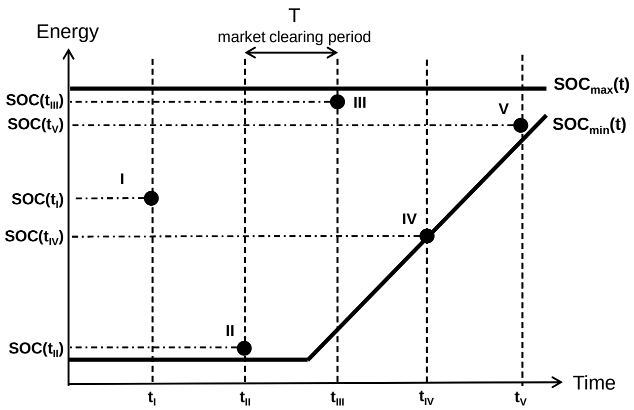


Fig. 3. Representation of the different use cases of an EV decision process regarding its individual power calculation

black curves represent the maximum and minimum state-of-charges (SOC). For each market clearing period, a particular SOC condition is represented for the vehicle considered. In each situation, the EV availability for frequency control purposes is assessed and the reserve power it can provide to the aggregator is also calculated.

I Situation I stands for the basic and most common situation: the EV is far from its SOC limits; thus it is available for frequency control and can offer a reserve power equal to its maximum power, i.e. its EVSE power level.

II In situation II, the EV's SOC is lower than the minimum SOC at next clearing time: $SOC(t_{II}) < SOC_{min}(t_{III})$. In this case, as the EV may need to charge for transportation before the next clearing time, the aggregator does not rely on it for the fleet's bids in the market, and the available reserve power from this EV is considered null. However, the EV can still be used to provide reserve power if necessary. This means that although the EV reserve power is not considered in the market bids, the EV charging power can still be used in real-time dispatching to provide the requested reserve power .

III In situation III, the EV is available for frequency control. However the power that can be offered is restricted to the maximum charging power that would fully charge the EV at the next clearing period $P_{bid_i} = \left(SOC_{max}(t_{IV}) - SOC(t_{III})\right)/T$. In a conservative scenario, extreme frequency deviations could require the EV to charge at full power for the entire market clearing period. By restricting the reserve power in this way, the aggregator makes sure that the EV will always be able to provide its full reserve power, even in conservative scenarios.

IV In situation IV, the EV is not available for frequency control as it needs to charge for transportation.

V Finally, in situation V, the EV will leave before the next market clearing time: the strategy is then the same as in situation II.

At the beginning of each market clearing period, each EV will compute its own available reserve power based on its SOC situation (I to V). Depending on the frequency value at each time stamp, the aggregator will then be able to determine the actual reserve power that should be provided for frequency control purposes.

All in all, these bidding strategies always ensure: (a) that all EVs will fulfill all their needs for transportation; and (b) that the total fleet power bid in the frequency control market is always lower than the actual available fleet power.

D. *Frequency data*

A frequency meter was used to build a frequency data set. One full month of frequency data were recorded at Centrale-Supélec in April 2014. These measurements abide by ENTSO-E requirements, i.e. they have a resolution better than 10mHz and the frequency measurement period is 1s. A summary of the frequency data set characteristics is provided in Table III. In order to check the consistency of the measurements, the characteristics of the recorded data set are compared over the same period of time with those of the RTE data set available on the RTE website [39] (which only has a 10-second time stamp, and this is why we were not able to use it).

TABLE III
MAIN CHARACTERISTICS OF THE FREQUENCY DATA SET USED, AND COMPARISON WITH RTE MEASUREMENTS

Criteria	*Author data set*	*RTE data set*	*Difference (%)*
Mean (Hz)	50	50	-0,002
Std (Hz)	0,02	0,02	0,4
Min (Hz)	49,9	49,9	-0,01
Max (Hz)	50,1	50,1	0
P(49,95<f<50,05)[a]	0,97	0,97	-0,22

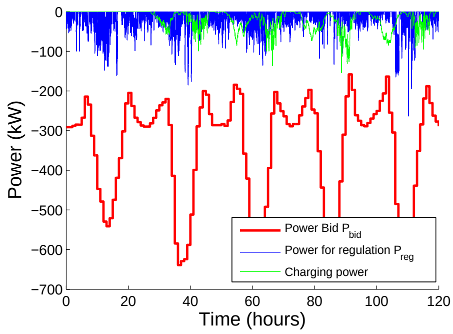
[a]P stands for *probability*

The two data sets turn out to share very similar characteristics. In particular, the frequency is contained in the interval [49.95Hz ; 50.05Hz] 97% of the time; within this interval, primary reserve units should only provide less than 25% of their reserve [38].

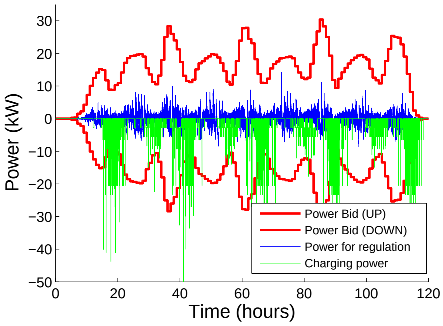
E. *Simulation scenario*

Two consecutive comparisons are conducted: first, the performance of an EV fleet operating in a symmetrical market is compared with the performance of an EV fleet operating in an asymmetrical market, with a market clearing period of 1h (section III-A). Then, on the basis of an asymmetrical framework, simulations for two different market clearing periods are conducted: one hour (as in the PJM regulation market) and four hours (as in the Energinet.dk primary control market) (section III-B).

For each use case, 100 simulations are run usinng the Monte Carlo approach for 100 EVs. One simulation consists of five continuous week days (from Sunday midnight to Friday midnight) of EV fleet behavior, including EV uses for transportation and EV participation in primary frequency control according to sections II-B and II-C, respectively. At the beginning of a simulation, the driving patterns for



(a) Asymmetrical framework



(b) Symmetrical framework

Fig. 4. Instantaneous power flow of the fleet for the different market designs, for one simulation. Y-axis feature different scales.

all EVs are determined using the parameters from table II, and five continuous days of frequency values are randomly selected from the frequency data set. Then, departure times and durations can be computed for each EV. At each time stamp (a time stamp of one second is used), the individual situation of each EV is assessed: if the EV is driving, then its battery energy is decreased by the corresponding amount of energy; if the EV is parked, it participates in the primary frequency control according to the strategy explained above. All EVs start with a SOC of 50%.

III. Results

A. Comparison between asymmetrical and symmetrical frameworks

The aforementioned simulations are performed for the asymmetrical and symmetrical frameworks. The aggregator and EV strategies are implemented respectively according to sections II-C2 and II-C3. The instantaneous EV fleet power flows (for one simulation) for asymmetrical and symmetrical use cases are shown in figures (4a) and (4b), respectively. The red curve represents the power that has been bid in the market, i.e. P_{bid}. The power actually provided for primary frequency control, P_{reg}, is depicted in blue. When EVs are not available for frequency reserves and they need to charge for transportation, their charging power is drawn in green.

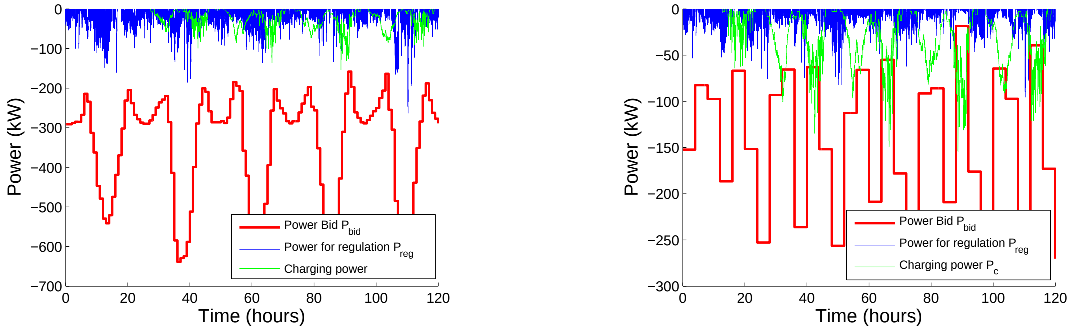
As EVSE power levels are higher at workplaces than at home (see table I), the power bid P_{bid} is higher during these periods. There are slight decreases in P_{bid} values before shifting from one location to the other because some EVs need to charge for transportation while others are being driven. The EVs start with a SOC of 50%. In the simulation represented in figure 4, it turned out that no EV trip required more than 50% SOC (12kWh); consequently, all EVs start with a SOC higher than their future needs for transportation. The power bid in a symmetrical market is then null at the beginning of the simulation and until the first departures (see equation 2). The power only used for charging is greater in an asymmetrical framework because EVs do not charge constantly as they do in a symmetrical market design.

It is striking on these curves how the power bid within an asymmetrical framework is much larger than in a symmetrical framework. On average, in the asymmetrical market design, the power bid is nine times as high as in a symmetrical situation. Table IV displays, for both market designs, the minimum, maximum, first, second and third quartiles of the power bid in the market P_{bid}. The results provided in table IV show that EV fleets with unidirectional capabilities only perform significantly better under an asymmetrical market design as opposed to a symmetrical market design. Regarding the symmetrical market, the minimum power bid in the market is 0kW, while it reaches 125kW under an asymmetrical configuration. For the same fleet, 75% of the power provided in the market is higher than 243kW in an asymmetrical market, while this value amounts to only 22kW under a symmetrical framework.

TABLE IV
Minimum, Maximum and Quartile values for P_{bid} for 1h market clearing time stamps

Market Design	*Min (kW)*	*Max (kW)*	*1st quartile (kW)*	*2nd quartile (kW)*	*3rd quartile (kW)*
Asymmetrical Market	125	675	243	281	441
Symmetrical Market	0	61	22	31	37

There is a significant difference in results between the asymmetrical and the symmetrical market designs. This difference resides in the fact that EVs need to charge constantly around a power setpoint to provide reserve power in a symmetrical dispatch framework. Consequently, even if only a small part of the fleet reserve power is used by the TSO, EVs are still charging, and inevitably become fully charged at some point. When an EV is fully charged, it is not able to provide reserve power any more, so the overall fleet reserve power decreases. On the contrary, in an asymmetrical market design, EVs are able to provide their maximum power as reserve power in the DOWN market. They will only charge as a result of frequency deviations, which happen to be restricted (see table III). It follows that EVs charge very slowly due to their participation in the DOWN market and are able to maintain a high level of reserve power much longer than in the symmetrical market design.



(a) Market clearing period of 1h

(b) Market clearing period of 4h

Fig. 5. Instantaneous power flow of the fleet with market clearing periods of (a) 1h and (b) 4h. Both Y-axis feature different scales.

B. Market clearing period sensitivity analysis

The previous section showed that, when only unidirectional capabilities are considered, an asymmetrical framework is much more suited for an EV fleet than a symmetrical one; it enables the aggregator to increase substantially its reserve power bids in the market. Here, only the asymmetrical framework is considered, and two different market clearing periods are selected: four hours and one hour. Simulations are performed as explained in II-E. Figures (5a) and (5b) show the results of one simulation test for the two market clearing periods. They highlight the fact that having a finer granularity enables the EV fleet to provide more reserve power.

In Table V, the minimum, maximum, first, second and third quartiles of P_{bid} are provided for both market clearing periods.

TABLE V
MINIMUM, MAXIMUM AND QUARTILE VALUES FOR P_{bid} FOR 1H AND 4H MARKET CLEARING TIME STAMPS. ASYMMETRICAL MARKET

market clearing period	*Min (kW)*	*Max (kW)*	*1st quartile (kW)*	*2nd quartile (kW)*	*3rd quartile (kW)*
1 hour	125	675	243	281	441
4 hours	19	271	70	133	202

The impact of having a shorter market clearing period is significant: the median power bid with a one-hour clearing period is more than twice as high as with a four-hour period. With a one-hour time stamp, 75% of the offers made in the market by the aggregator exceed 243kW, while they only exceed 70kW with a four-hour market clearing period.

IV. DISCUSSIONS

Each year, TSOs spend a significant amount of money to procure the amount of primary reserve they need. For instance in France, with a regulated tariff of 16.96€/MW-h [40] and a primary reserve amounting to 600MW [41], the primary reserve procurement comes to approximately 90 million Euros each year to RTE (which, ultimately, are spread out over all final customers). When the procurement method is an auction, it is difficult to assess the costs of each reserve providing unit, because they do not necessarily bid at their marginal costs. However, in the case of an EV fleet, it is likely that the cost of providing primary reserve power will be low. Indeed, with unidirectional capabilities, the only additional hardware required would be a frequency meter. Apart from that, the remaining costs are: communications costs (quite low because existing communication networks can be used) and risk management costs. Thus, if the share of the whole reserve provided by EVs rises, and if EVs were actually proved to be cost-effective reserve providing units, reserve clearing prices would naturally go down. Obviously, TSOs would bear the costs of changing their market rules; however, these costs should remain low in comparison with the savings achieved , and proof of the availability of the reserve must be provided.

Apart from lowering reserve costs, EV fleets could also increase the overall available reserve power for the TSOs. This could be helpful to some systems in order to integrate more Variable Resource Renewable Energy (VRRE).

It is worth noting that the solution proposed in the paper is implementable in real-life. Indeed, a possible solution would be to have each EV read the frequency locally and respond automatically to frequency deviations. In this situation, EVs and the aggregator would need to communicate every hour (for the EV's available power for primary frequency control), and from time to time if the EV conditions are updated by the users. In the light of these constraints, current communication standards already make it possible to implement this solution[6].

The proposed bidding strategy ensures that the aggregators will always be able to fulfill their bids, irrespective of the frequency deviations (see section II-C3). However, unanticipated events (such as several EVs leaving unexpectedly at the same time) could prevent the aggregator from dispatching the required reserve power. In such a situation, the aggregator would be charged with penalties, whose size varies from one TSO to the next. In real life, aggregators would try to smooth out these risks by using statistical analysis and by relying on a large number of EVs in their fleet.

The present study is based on trip-related data collected in 2008. As a consequence, the EV trip modeling depends on the assumption that mobility patterns have not changed since 2008. The use of personal vehicles has remained largely

[6]Such standards would be the ISO IEC 15118, OCPP, OCSP, etc.

unchanged among French people who have owned their vehicles since the 2000's, as shown in [42]. However, new car uses such as car-sharing or long-term car-leasing are now emerging, especially in urban areas – where EVs are also likely to develop. A partial shift from an ownership economy to a sharing and use economy has been observed recently. Rather than buying a vehicle, some people are today more interested in buying mobility services, and even car manufacturers have started to offer such services. In this situation, selling mobility services together with energy services would make good sense. However, the driving patterns of shared vehicles will be very different – in particular, more intensive uses are expected – and they are more difficult to predict. The aggregator will have to deal with several users' preferences, and more uncertainties. Business models and revenue sharing will be more complex. Similarly, long-term car leasing raises important questions about revenue sharing between the EV user and the EV – or battery – owner.

The present study focuses on private EVSEs, where EVs have plenty of time to charge because they are not expecting another EV to charge at this EVSE. Considering a public infrastructure network, the problem would be significantly different. A trade-off would have to be found between slowing the EV charging rates in order to participate in the reserve market, and increasing the charging rate in order to charge as many EVs as possible with the current infrastructure.

V. Conclusion

In this paper, the possibilities of an EV fleet with exclusively unidirectional capabilities participating in the primary frequency control market were investigated. The main findings are twofold: first, considering unidirectional capabilities only for EVs, the power that can be bid in the market is much greater under an asymmetrical than under a symmetrical market design. Then, the impacts of having a shorter market clearing period are significant: the median power bid is twice as high with a one-hour clearing period as with a four-hour period. Considering these results, System Operators (SO):

1) could make every endeavor to allow the integration of Electric Vehicles fleets into their frequency reserves, as they are proved to be efficient reserve providers;
2) could procure upward and downward products through separate markets;
3) could reduce the product duration.

By doing so, SOs could lower their reserve purchasing costs, and increase the maximum Intermittent Renewable Energy Resources (VRRE) penetration level allowed.

The approach presented in this paper could be extended to all Distributed Energy Resources (DERs). Indeed, EV fleets were selected as an example, but other DER types such as stationary storage units, distributed generation, micro-CHP units, could also be efficient reserve providers. All DERs have different attributes and characteristics, what could make them complementary. For instance, EVs which do not have the ability to charge at workplaces are available for grid services at night only; on the other hand, workplace cooling / heating systems are available during the day.

Likewise, the rationale of the paper could be extended to other grid services. Apart from primary frequency control, TSOs implement various mechanisms to balance production and demand: secondary and tertiary frequency controls, balancing mechanisms, spinning reserves, bulk electricity market, etc. DERs could participate in all these markets provided that TSOs adapt their market rules. Similarly, Distribution System Operators (DSOs) should promote solutions that would enable DERs to participate in local voltage control and congestion management.

Such a complete framework, allowing most DERs to participate in local and system-wide grid balancing mechanisms, would help stabilize the grid and enable a higher VRRE penetration.

Future work could consist in building more complex EV driving patterns. First, driving trips could be extended to other purposes than work-related trips. Second, a distinction could be made between car use and car ownership, taking account of emerging car-sharing and car-leasing solutions. Similarly, other initial conditions could be tested: for instance, sensitivity analysis could be conducted on the initial SOC of each EV.

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