Simulation of Electric Vehicle Battery Behaviour for Frequency Regulation Use: Profitability Versus Mobility Constraints and Grid Needs

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***Abstract*—Electric Vehicles Batteries are particularly adapted for frequency regulation service regarding their features and their availability. Many parameters have an important impact on the service profit like the grid needs, the driving patterns, the battery wear, the investments and the service remuneration. The aim of this study is to propose an algorithm in view of dynamic simulation taking into account grid requests, vehicles driving patterns and the electricity prices. The proposed tool can use real Electric Vehicles and grid data as well as simulated ones. It allows apprehending the profitability for various markets situations, mobility patterns and charging schedules. It also allows following the gains during the day in view of gains communication to the Electric Vehicle or fleet owner and for a dynamic decision about the service delivery depending on the profit and the battery availability.**

Keywords-Vehicle to Grid; Frequency regulation; Profitability calculation; Dynamic simulation; Regulation market remuneration.

I. INTRODUCTION

Nowadays, the widespread use of Electric Vehicles (EVs) faces many difficulties due to their high prices and their limited autonomy compared to vehicles that use fossil fuels. However, with the foreseen advancements in storage technologies, EV will be an important tool under the context of smart grids to improve efficiency and sustainability of power systems. Indeed, it may be a very relevant means to provide grid services in order to better manage, with the uncertainty of renewable generation, grid congestions as well as using the batteries energy for other grid services. In fact, the vehicles are used 5% of the time for mobility and are available for other purposes during the remaining time [1]. Consequently, a good storage potential will be available according to the development of EV. On the one hand, the EV battery can support the intermittent renewable sources of energy by absorbing the production when there are no consumption needs in the grid. At the same time, the used energy for mobility will come from green sources ensuring the low carbon footprint of the EV.

On the other hand, the EV battery can help the grid for balancing production and consumption and ensuring power quality. In fact, the available energy can be used for ancillary services like frequency regulation or peak shaving.

In the context of Vehicle to Grid (V2G), an EV fleet acting like a generation unit is an interesting actor in the energy markets like in Germany and Sweden [2], California [3] or France [4]. Studies also proved that a single EV is able to provide ancillary services under real-time conditions [5] in the PJM market, which coordinates electricity in 13 states in USA and the District of Columbia.

Some studies [6] highlighted that the peak power management corresponding to power injection in the grid during high consumption periods is more suitable with hybrid vehicle regarding the high amount of needed power versus mobility constraints and battery wear. Nevertheless, other ancillary services are very suitable for EVs batteries in particular frequency regulation [7] [8] characterized by low amount of energy requests many times during the day.
Studies show gains between 100€ per year per vehicle in the French context [4] and 2000€ in the American one [3]. The EV battery is profitable for frequency regulation service because the initial capital cost of the battery purchased for driving may not be totally assigned to the V2G [1]. Besides, the battery response time is quick [1] [3] and the low quantity of energy induces shallow cycling and thus extended life cycles [9]. However, the profitability for several actors like the DSO, EV aggregator and EV owner must be ensured and is variable depending on the context. The profitability may concern EV owner or EV fleet aggregator. For the EV owner, the service may be profitable at his level if a single-vehicle is able to provide the service under real-time conditions in the regulation market. Otherwise, his gain will be shared with an EV fleet aggregator able to offer a higher level of power to the grid.

This paper aims to present an interesting tool allowing the simulation of the dynamic behaviour of an EV Battery (EVB) while ensuring, mobility and frequency regulation service. The proposed algorithm calculates the service availability and the net profit for each request of the grid.

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The first part of this article describes the frequency regulation service and some regulation markets in the world. The second one presents a detailed description of the profitability calculation methodology by request. The third part presents the algorithm allowing simulating the EVB behaviour during one day including the availability and the profitability. It also presents the used algorithm to generate the driving patterns that are one of the main inputs of the frequency regulation simulation. The other parameters and inputs are also described. Finally, realistic case studies compare the profitability for various situations. They illustrate the possibility of using the proposed tool in any context to simulate the EV behaviour under mobility and services constraints. It can also integrate real EV data to calculate the service profitability and to decide about the service delivery.

II. FREQUENCY REGULATION

The grid power quality is dependent on the real time balance between the electric consumption and the production while maintaining, for instance, rated voltage, frequency and harmonics level. Regarding the frequency regulation, it is dependent on the balance of active power in the grid. In fact, the frequency decreases if the consumed active power exceeds the generated one, thus, there is a need of “regulation up”. Contrariwise, if the generation exceeds the consumption, frequency rises and a “regulation down” is necessary. In order to achieve these operations, three frequency reserves exist: the primary and the secondary reserves, which are generally automatic, and the tertiary reserve or long-term reserve, which is triggered manually.

The primary reserve is for an instantaneous adjustment (seconds) and activated automatically. Today, this regulation is implemented via the speed regulation of the production groups and the frequency of use is high. Obviously, as EVBs can offer the primary regulation, they are also able to offer secondary and tertiary ones. However, this study will concentrate on the primary regulation.

Regarding the high amount of needed power at grid level compared to each EV battery capacity, new actors like EV aggregators will allow optimizing EV resources as storage. For the fleet manager, one of the main issues is the real available power for the service. In fact, EVBs may not be plugged in or not with the right State of Charge (SOC). In this context, various studies on the stochastic behaviour of EVs stated the reliability of the frequency regulation service despite the mobility constraints [10].

A. Markets

Regarding the regulation market, we talk about Automatic Generation Control Market (AGC) in most of the countries. In the smart grid context, new grid components offer regulation services in the regulation market like controllable loads or electric storage. For instance, CAISO Market allowed Non-Generator Resource (NGR) such as batteries and flywheels, to bid in the regulation market [11]. Batteries are well positioned in the AGC market by nature because the time response of the electric storage is fast and adapted to high quality primary frequency regulation. The California Energy Commission stated that the storage resources are at least twice as effective as a combustion turbine for the grid regulation purposes [11].

The payment of regulation services is represented by various prices depending on the markets [12]. Most of them take into account capacity price for the energy made available for the service and service price for the effective supplied energy. For instance, in the ISO New England (ISO-NE), the payment includes capacity price and service price [13]. Some of the markets use only one of the two remunerations as in France where the primary reserve payment is provided by a fixed tariff and the payment is limited to a capacity price whereas secondary reserve includes both of the capacity and service prices [4].

The regulation market functioning is highly dependent on the electric grid features. It mainly depends on the geographical location, the renewables’ penetration, the EVs presence. Besides, it is also impacted by the advancements in the smart grid installations with possibilities of grid services offers based on storages, load management and other means. Many markets are under development or are currently changing depending on the grid situations.

III. PROFITABILITY CALCULATION

In this part, the annual net profit calculation [3] is extended to profitability calculation per grid request.

A. Per request revenue calculation

In the case of V2G used for frequency regulation, the capacity payment is for power being available in kW-h to support the grid. Whereas the energy payment is for the energy in kWh exchanged in real time. The per request revenue is calculated using the following equation:

$$R_{reg-r} = R_{el-r} + R_{cap-r} = \left(p_{el}\, Q_{request}\right) + \left(p_{cap}\, P\, \frac{h_{plug}}{T_{day}}\right) \quad (1)$$

For the remunerated produced energy per request R_{el-r}, the delivered energy $Q_{request}$ in kWh is multiplied by the electricity price p_{el}, which is the market selling price of electricity in €/kWh.

Besides, the capacity payment R_{cap-r} is calculated using:

- p_{cap}, the capacity price, which is in €/kW-h. It is the price for the service availability, it means the remuneration fixed by the contract for the participation to the service when the battery is plugged in and available. There is a remuneration even if there is no service.
- P is the contracted capacity available for the V2G, in kW. It is the smallest value between vehicle power P_{veh} and the line power P_{line} because both of them limit the power. P may also be limited by the performance represented by the response ramp dynamic. The ability of ramping limits the total amount of power capacity in some markets like PJM [14]. Nowadays, 95% of the charging stations are slow charging for instance

in France 3kW [15]. For V2G participation, fast charging is more interesting. We assume a value of 15kW with adapted installation [3].
- T_{day} is the number of transfers per day.
- h_{plug} is the number of hours during the day when the EV is plugged in and available for the service.

In regulation down, we assume that the operation is always financially positive because the battery will have to be charged for mobility purposes. In fact, if the SOC matches with the demand, the regulation down is achieved, and the gain corresponds to the stored energy E_{sc} (kWh) multiplied by the price of buying the electricity c_{pe} (€/kWh) at the charging moment. The gain represents the charging cost if it had been realized using the grid.

B. Per request cost calculation

The cost for regulation up is defined as follows:

$$C_{reg-r} = C_{el-r} + C_{c-r} = c_{en}\, Q_{request} + \frac{c_{ac}}{T_{day}\, d_{plug}} \qquad (2)$$

Regarding the energy cost C_{el-r} calculation:
- c_{en} is the cost per energy unit in €/kWh, which includes: the cost of electricity, losses, plus battery degradation cost. It is calculated as follows:

$$c_{en} = \frac{c_{pe}}{\eta_{\ conv}} + c_d \qquad (3)$$

Where c_{pe} is the cost of purchased electricity for recharging in €/kWh. η_{conv} is the two-way electrical efficiency and is around 73% [3].
c_d is the cost of battery degradation calculated using :

$$c_d = \frac{c_{bat}}{3\ L_c\ E_s\ DOD} \qquad (4)$$

- L_c is the number of cycles fixed to 2000 cycles for Li-ion battery at 25°C [9].
We assume that shallow cycling has less impact on battery lifetime than deep cycling [3] [7]. Thus, factor 3 is used for the number of cycles.
- DOD is the maximum Depth of Discharge in % fixed to 80% [9].
- c_{bat} is the total battery replacement cost in €, calculated using:

$$c_{bat} = (E_s\, c_b) + (c_l\, t_l) \qquad (5)$$

Where c_b is the cost of the battery in €/kWh assumed to be $c_{b\,=}$ 300€/kWh [15].
c_l is the cost of labour in € and t_l the labour time required for battery replacement. They are fixed to the average of the labour cost, in 2015 in Europe it was 35€/h [16] and a replacement labour time of 8 hours [3].
- E_s in kWh is the energy of the battery fixed to 22 kWh, which represents 65% of EVs in France in 2013 [15].

For the capital cost calculation C_{c-r}:
- c_{ac} is the annualized capital cost for additional equipment needed for V2G calculated using:

$$c_{ac} = c_c\, CRF = c_c \frac{d}{1-(1+d)^{-n}} \qquad (6)$$

- c_c is the capital cost i.e., the one-time investment assumed to be 1800€ including on board metering, adapted power electronics for V2G, wireless communication system, and wiring costs [3].
- CRF is the capital recovery factor calculated using *d*, which is the discount rate in % and n the amortization duration in years thus the lifetime of the V2G hardware fixed to 10% and 10 years [4].
- d_{plug} is the the number of days in the year when the EV is plugged in and available for the service.

The cost from regulation down is assumed to be null because there is no need of additional equipment and it is considered as always interesting because it is free charging.

IV. Simulation Algorithms

The frequency regulation simulation algorithm is implemented in Matlab. To make it available under SEAS Shared Intelligence Platform (SEAS-SI), developed by GECAD for SEAS project [17], inputs and outputs templates, as well as specific web services, needed to be developed accordingly. SEAS-SI platform allows algorithms sharing without confidentiality concerns. Those algorithms may be executed on-line, alone, sequentially or combined differently. The EV behaviour algorithm outputs are used for the frequency regulation simulation.

A. EV behaviour algorithm

Electric Vehicle Scenario Simulation tool (EVeSSi) has been actively developed since 2011 [18] with the goal of supporting the development of realistic case studies that include scenarios with EVs, eliminating the need to create manually each individual vehicle profile.

EVeSSI includes several modules: scenario and input configuration, SUMO simulation, SUMO output data importer, electric grid creator, and an intelligent grid allocator. In the first stage, EVeSSi is used essentially as a parameterization tool to introduce the input data for the simulation in SUMO. These inputs can be summarized as follows: the first step is to generate/load the road network (load a real road network or generating a “virtual” one by introducing specific parameters), a second step is related to the creation of EVs and its parameters, and then it is necessary to specify the charging points or use a random generation to do it. Finally, an algorithm can perform the daily activities and generate the necessary trips, which are then simulated by SUMO engine (the actual traffic simulation results). The data importer module reads the files generated by SUMO application and then filters, treats and analysis the necessary data to be executed by the subsequent developed algorithms. The grid creator can generate an electric grid taking into account the dimensions of the road network. This creates a grid with intelligently distributed electrical buses and respective branches. This algorithm is used only if the user does not specify a local real grid. If the user loads the respective real grid the mentioned generation is skipped. After this step, the intelligent grid allocator finds the corresponding electric bus where EV can connect, depending on the location, i.e., the street of the arrival or where it is parked.

The traffic model allows evaluating the chaotic behaviour of traffic, which is affected by several factors, including the road network topology, the number of cars and their routes, the types of vehicles, traffic lights and the users' driving behaviour, which is hard to predict. The influence of traffic patterns in travel times can be analysed, and the energy consumption measured. The integration of the traffic model with EVeSSi enables to bridge the road network and the electricity grid, therefore, overcoming the existent gap in current applications [19]. In fact, there is a huge potential in applications with EVeSSi, for instance, evaluating performance of electric public transports, analysing optimal location of charging points and charging stations, estimating electricity network impacts, testing different control strategies like smart charging and V2G approaches, predicting traffic patterns and user behaviour, among others.

B. *Frequency regulation algorithm*

There are three main loops in the frequency regulation algorithm (FreqReg). The first one decides about the EV availability for the service mainly according to mobility and charging constraints. The second one deals with frequency up requests and the third one with the frequency down requests. During all the simulation, the SOC is calculated according to the delivered services, the mobility and the charging. However, for a real EV, the SOC may be given by the EV Battery Management System using adequate communication solutions when possible. ISO 15118-2015 defines the bidirectional communications protocol for the Vehicle to Grid communication interface. It prepares a standardized context for EV integration to the power grid. For instance, communication requirements for energy demand/response information (local and grid) as well as vehicle charge status are defined. In our simulation, the algorithm inputs are described in Fig.1.

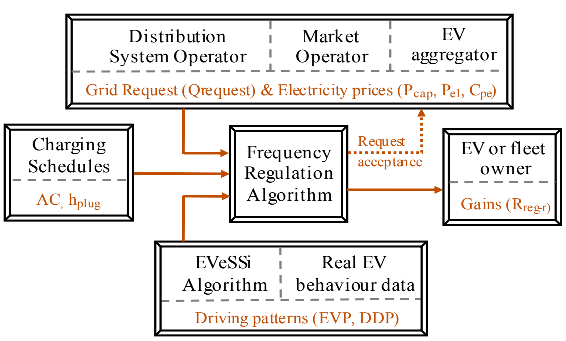

Figure 1. Frequency regulation algorithm interactions

1) *Availability for the service request:*

The algorithm decides about the availability of the EV for frequency regulation service:

If the EV is not used for mobility and if it is plugged in and not charging, the EV is available for the service, thus, the capacity payment R_{cap-r} and the capital cost C_{c-r} are calculated.

If the EV is not available, the SOC is calculated as follows:
- In case of mobility use, using the vehicle driving efficiency η_{veh} in (kwh/km) and the travel distance (km).
- In case of charging, according to the charger features.

2) *Frequency regulation up/down:*

If the EV is available and the grid demand is to supply/store energy, the request is for frequency regulation up/down. The loops calculation is as follows:
- The available energy E_{sa} /storage capacity E_{sc} is calculated using the last calculated value of the SOC:

$$\begin{cases} E_{SC} = E_S\,(1 - SOC) \\ E_{sa} = E_S\,\left(SOC - \left(DRB + (1 - DOD)\right)\right) \end{cases} \tag{7}$$

DRB is the distance range corresponding to the EV owner needs for mobility. Daily trips in Europe and USA are around 40 km [4]. Thus, for a typical working day, the average driven distance "home to work" is about 20 km. Nonetheless, people will probably overestimate their needs [15].
- If the battery SOC matches the demand, the service is realized, thus, the energy payment R_{el-r} and the energy cost C_{el-r} are calculated.
- If the battery capacity does not match the demand, an offer is made with the available energy / storage capacity and the EVB is waiting for a new grid request.
- The new SOC is calculated after the service delivery.

3) *Simulation inputs:*

All the algorithm inputs are vectors with length i representing the number of requests per day.

a) *Driving pattern:*

The inputs describing the EV behaviour are:
- The vector "EV Plugged in" is: EVP = $[EVP_1 \dots EVP_i]$
$EVP_i = 1$ if the EV is plugged in and $EVP_i = 0$ if the EV is on the road or parked but not plugged in.
- Driven Distance per Period in km: DDP = $[DDP_1 \dots DDP_i]$

EVeSSi outputs are the EV status regarding mobility with the consumed energy, the driving hours and the connection to each bus. Thus, it is useful to define EVP and DDP vectors. The data-set generated using EVeSSi contains 1800 realistic EVs and PHEVs with a 24h-period scenario and a step time of 1h. It is available as "Case with 1800 EVs / GECAD" in IEEE-PES Working Group on Intelligent Data Mining and Analysis [20]. There are 180 EVs and we are focusing on three representative types of vehicles:
- Type 1: 1h of daily trip with a round trip and a total of around 20 km. It represents the average of 40% of the 180 EVs of the database. For the simulation, we use EV n° 39 – Bus n°30;
- Type 2: 2h of daily trip with two travels and an average of 20 km per travel. It represents a typical working day in Europe and USA [4]. For the simulation, we use a total of 46 km – EV n°19 – Home (Bus n°7) – Work (Bus n°11);

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- Type 3: 2h of daily trip with high mobility needs with two travels. For the simulation, we use a total of 165 km – EV n°179 – Home (Bus n°3) – Work (Bus n°22).

b) Charging:

The charging vector is called “Availability to Charge”: AC = [AC_1 … AC_i]; AC_i = 0 for EVB not available for charging and AC_i =1 for EVB available for charging.

In our case studies, the EV is charged during the low electricity price hours depending on the mobility constraints. Otherwise, the algorithm allows integrating any smart charging schedule.

c) Grid requests:

The energy needs, at each request, are:

- $Q_{request}$ = [Q_{req1} … Q_{reqi}]

The DSO fixes its needs in kWh for frequency regulation up and down. Our simulation can be realized for any grid needs. Our studies highlighted a slight annual profit difference of 21 € per year between summer (2015/07/19) and winter (2015/02/25). Thus, the results are presented for winter day to investigate the parameters impact. The data is available on RTE (French DSO) data base [21]. Requests are given for each half an hour thus 48 requests are simulated per day. The inputs may also be recuperated in real time through the right communication devices with the DSO or the aggregator. In our approach, we assume 100 000 EVs under contract and carrying out the half of the frequency regulation demand.

d) Remuneration and prices:

- P_{cap}= [P_{cap1} … P_{capi}]. We use a constant capacity price P_{capi}= 0,017€/kW-h, representing of the French market. However, the remuneration level will certainly change in the next years and may become variable [4];

- P_{el}= [P_{le1} … P_{eli}]. We assume a constant price of P_{eli}=0.05€/kWh. It is a mean value of the electricity price in EPEX database in 2015 (average for one day by season) [36]. This value is mainly dependent on the regulation market and may vary during the day;

- C_{pe}= [C_{pe1} … C_{pei}] is the electricity price for charging the battery fixed to EPEX values [22].

V. CASE STUDIES

A. Mobility

Fig. 2 represents the grid requests for one EV and for the 25th February 2015. It represents regulation up requests with positive values and regulation down ones with negative values.

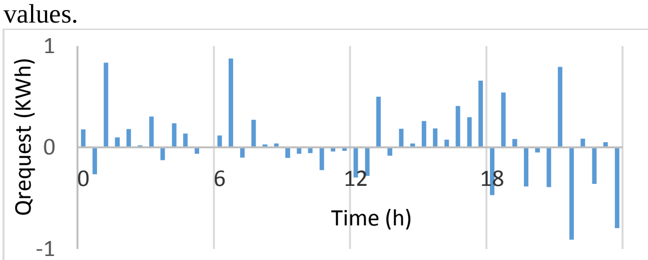

Figure 2. Grid requests for one EV, 2015/02/25.

Fig. 3 represents the batteries of the three types of vehicles submitted to grid requests, mobility and charging.

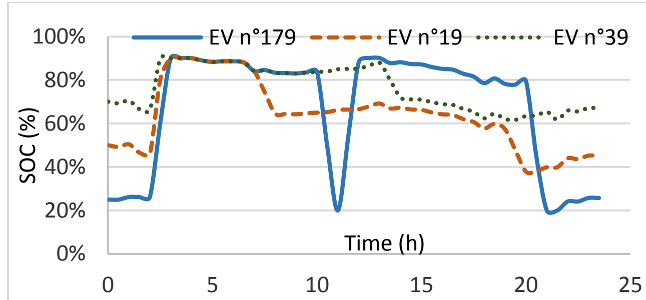

Figure 3. EVs batteries State of Charge (SOC) variation, 2015/02/25

Regarding the EV n°39 (20km) and n°19 (46km), the SOC decreases according to the mobility of the day. Otherwise, the EVB is available for frequency regulation service except during the charging scheduled during the night taking advantage of low electricity price period. Fig. 3 shows that the regulations up and down have very low impact on the SOC regarding the low amount of energy and the compensation of the two kinds of requests. We notice that there is no need of charging during the day to allow the EV owner to ensure its requirements regarding mobility.

The net profits for one day are as follows:

- For EV n°39: 4,4 € per day (1 606 € extended to 1 year).
- For EV n°19: 4,2 € per day (1 533€ extended to 1 year).

The net profits are very close. The main part of the gain is coming from the capacity remuneration (around 80%), which is impacted by the EV availability to offer the service. This conclusion is true under the adopted remuneration conditions, however it may be completely different in other contexts where the capacity price is low or does not exist.

The EV n° 179 has more important mobility needs. Consequently, charging is necessary during the day to ensure the second trip of the day and is scheduled after the end of the first trip. The EV offers frequency regulation during the rest of the day and as for the previous cases, the service impact has low impact on the EV SOC. The net profit per day is around 3,7€ (1 350€ extended to 1 year). The benefit is lower than for the other EVs because of the lower availability of the EV due to the charging period and the mobility constraints; however, the gain is still very interesting.

B. Charging and V2G equipment

EV owners may plug the EVB at home on their primary EV Supply Equipment (EVSE) or at work on their secondary EVSE. Nevertheless, EVSE may not be available at work. Besides, even if the EV owner decides to participate to the regulation market through V2G investment at home, he is not ensured to have this possibility everywhere.

Thus, we consider two scenarios for the same grid requests in Fig. 4:

- C1: EV n°19 with EVSE at home and at work.
- C2: EV n°19 with EVSE only at home.

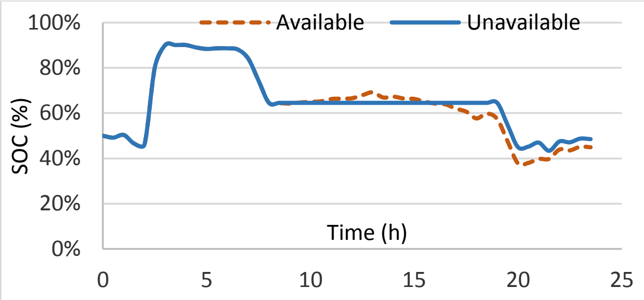

Figure 4. EV n°19 battery State of Charge (SOC) variation 2015/02/25.

Notice that because the EV is not plugged in or because the V2G service is not possible, EVB SOC is not affected when the driver is at work. Fig. 3 also highlights the low impact of the service on the SOC. However, this situation has an important impact on the profit, which is about 1,43€/day (522€/year). In fact, the driver cannot offer the service at work, thus the plugged in time is low inducing no capacity payment and thus the net profit drop.

VI. CONCLUSION

The proposed algorithm is an interesting tool allowing simulating the frequency regulation service offered by Electric Vehicle Battery. In fact, it allows the dynamic calculation of the service availability as well as the net profit taking into account the service cost, the service remuneration, the grid needs and the mobility constraints for each request during the day. The simulation approach takes into account the mobility patterns obtained thanks to the simulation algorithm EVeSSi. Otherwise, the real EV SOC can be obtained using adapted communications means with the Battery Management System when possible. Besides, the algorithm allows varying the market remuneration conditions during the day; therefore, it is adaptable to various energy markets conditions. The results highlight that the service profitability is interesting even with high needs of mobility. In fact, in a regulation market where the capacity price exists, one of the most important parameter is the availability of the EV. In contrary, if it is low or does not exist, the electricity price becomes more important in the net revenue. One of the main parameters that may affect the frequency regulation net revenue is the unavailability of the adapted EV Supply Equipment. The regulation markets are very different in the world and the smart grid context changes them. The proposed simulation tool is helpful to predict the dynamic net profits evolutions according to the varying prices and the EV owners' behaviours.

Finally, the algorithm outputs can be used to make the EV or fleet owner aware of the gains through adequate interfaces in order to support the incentive nature of such participation. They can also be used for the communication with the grid in order to decide about the service availability depending on the SOC level and/or the profitability. Forthcoming studies aim to include smart charging schedules in the simulation to apprehend their impact on the frequency regulation profitability. Besides, in the real time context, it will be interesting to investigate the algorithm functioning including all the estimations and optimizations that could be interesting to add in order to achieve various V2G services.

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