CONTRIBUTION AND IMPACTS OF GRID INTEGRATED ELECTRIC VEHICLES TO THE DISTRIBUTION NETWORKS AND RAILWAY STATION PARKING LOTS

Siyamak SARABI, L2EP-HEI – France, ADEME - France, siyamak.sarabi@hei.fr
Arnaud DAVIGNY, L2EP-HEI – France, arnaud.davigny@hei.fr
Yann RIFFONNEAU, SNCF-I&R - France, yann.riffonneau@sncf.fr
Vincent COURTECUISSE, GEREDIS - France, vcourtecuisse@geredis.fr
Benoit ROBYNS, L2EP-HEI - France, benoit.robyns@hei.fr

ABSTRACT

This paper presents the contribution of electric vehicles to the distribution grid and railway station parking lots and their uncontrolled charging impacts on these grids. The economic indicators have been chosen as performance criteria. The benefits and advantages of using the charging/discharging coordination in sense of economic indicators have been evaluated by using mixed integer linear programming and interior point for nonlinear optimization. The impacts of different charging scenarios have been evaluated and the results show high interests of using coordination charging techniques and V2G technology for grid service providing.

INTRODUCTION

Nowadays, the concept of smart grid and its definition, application, impacts and contribution to the conventional electrical grid are widely discussed in academic and industrial societies. The problem of traditional energy sources restrictions, their environmental impacts and technical criteria improvement of electrical grids lead to introducing new concept of grids which have bidirectional contribution between production and consumption. In such idea, the presence of renewable energy sources such as solar and wind and electric vehicle (EV) with vehicle-to-grid (V2G) technology become highlighted. These distributed generation sources can be stored in peak hours and reused during off-peak hours. On the contrary, it is important also to take into consideration the unwanted impacts of growing electrified transportation on the electrical grid, due to the coincidence of daily load peak and charging time of EVs [1]. In France, a perspective planning estimates 2 million electric vehicles up to 2020 [2]. ERDF, an electricity distribution network company in France for a fleet of 1 million EV has estimated 2.5TWh annual energy consumption during charging process, which counts 0.5% of total consumption in 2013. While, in sense of instantaneous power demand for case of rapid charging with 43 kW charging power, 47 % of available power of the national grid can be solicited. This can be reached up to 100% at MV and LV distribution network level [3]. To cope with upcoming issues due to this large demand, the implementation of charging infrastructures and supervised intelligent charging/discharging energy management strategies are in hand projects for future. In order to define potentials of electric vehicles to respond to the grid services, the impacts of different scenarios, containing coordinated and uncontrolled charging at different operational modes, should be taken into consideration.

In this paper, the impacts of uncontrolled charging of EV fleets and coordinated charging planning with optimization will be analysed on two case studies. The first case is a railway station which is serving the EV charging infrastructure in its parking (20/0.4 kV) and the second case is a distribution grid at a distribution substation level (90/20-15 kV). Both cases will be presented precisely thereafter.

The remainder of this paper is organised as follow. First of all, the charging profile of electric vehicle fleet considering their arrival SOC, driving distance and battery capacity are calculated. Secondly, the uncontrolled charging scenarios for each case study with their specifications will be presented. Afterward, the contribution of EV fleet by charging coordination and V2G capacity offer will be explained for each case study. Then the results and comparison will be addressed and finally the paper will be concluded.

ELECTRIC VEHICLE CHARGING PROFILE

Plug-in electric vehicles charging process depends on different criteria: battery capacity and autonomy of the vehicle, arrival state of charge (SOC) and desired departure SOC and charging power rate of the charging system. In France, three charging power rates based on the location and occasion of charging have been considered.

These configurations are based on IEC 62196 which is an international standard for set of electrical connectors and charging modes for electric vehicles maintained by International Electrotechnical Commission [4]. Normal Charging (NC), a single phase AC charging with 3 to 3.7 kW charging power rate, Accelerated Charging (A.C.), a three phase AC charging with 23 kW charging power rate and Rapid Charging (RC), a three phase AC charging with 43 kW charging power rate. In this study, we assumed to have basic information for calculation of charging profile of EV fleet for each case study. To calculate the charging profile following equations should be considered [5].

$$SOC^i_{arrival} = \left(1 - \frac{D^i_d}{Au^i}\right) \times 100\% \quad (1)$$

$$E^i_{G2V} = (1 - SOC^i_{arrival}) \times E^i_{EV} \times \eta_c \quad (2)$$

$$T^i_c = \frac{E^i_{G2V}}{C^i_r} \quad (3)$$

$$CP_i(k) = \begin{cases} C^i_r \, , & T^i_s < k < T^i_s + T^i_c \\ 0 & , \; eslewhere \end{cases} \quad (4)$$

$$P_{fleet}(k) = \sum_{i=1}^{n} CP_i(k) \, , \qquad 1 < k < 144 \quad (5)$$

Where in (5) arrival SOC is calculated based on D_d^i driving distance of EV i and Au^i the autonomy of the same EV. E_{G2V}^i is the energy needed by the same EV to be fully charged with its battery capacity of E_{EV}^i in kWh and charging efficiency of η_c. The charging time T_c^i of this EV can be obtained from its energy need and charging rate C_r^i of the charging station (C_r^i can be 3, 23 or 43 kW based on chosen type of charging).

UNCONTROLLED CHARGING SCENARIOS

In the concept of uncontrolled charging of EV fleet, there is no control signal from supervision system through charging infrastructure to the EV plugged-in to the grid. In other words, like most of the electric devices the users can charge their device's battery just by plugging the device in to the socket and charging process will start instantaneously. This can be the same for EV arriving to home, office or public charging stations and simply start to be charged just by being plugged-in. In this study, we have considered that all the EVs just after their arrival time will be plugged-in and charged. The types of electric vehicle considering in this study are based on current EV market contribution of different EV producers in France [6]. In addition the daily driving distance based on statistical data is normally distributed between 10 and 50 km per trip. The two case studies with their characteristics and charging scenarios are as follow;

Case A: Railway Station Parking Lots

The railway stations in France are the subject of smart grid developments with possible energy interactions between the grid and the users. Their connection to the distribution grid is through a MV/LV substation with range of 20-15/0.4 kV. These stations are supposed to act as an energy hub with different components such as local Renewable Energy Sources (RES) and electric vehicle charging stations. To analyse the impact of daily arrived EV to the parking, different scenarios have been considered. In this study the possibility and contribution of coordinated charging/discharging is also taken into account. These scenarios are based on arrival time and departure time of the EVs to the parking. The arrival time of the vehicles are distributed normally between 7:00 to 9:00 whereas the departure time is distributed normally between 16:00 to 20:00. The average availability interval is around 10 hours during which EV can be used for charging coordination. The total number of 10 charging station has been considered as base case. The capacity of the railway station is also evaluated from 1 to 50 charging stations. Charging stations are divided into several types of charging process, different cases have been studied and are described as follow;

Normal Charging (NC)

Normal charging case is the principle charging option for majority of EVs with 3 to 3.7kW charging rate. For an EV with 20 kWh battery capacity, it takes 6 to 8 hours to be fully charged. In this scenario all the vehicles arriving to the parking will choose NC charging mode.

Accelerated Charging (A.C)

Accelerated charging case is the charging mode with three phase circuit and 23 kW charging rate power. For an EV with 20 kWh battery, 1 hour is enough to be fully charged. In this scenario all the EVs are considered as choosing AC charging mode.

Rapid Charging (RC)

Rapid charging is the case for charging station in highways and freeways where the users need to have their battery fully charged very short. Charging rate of 43 kW lead to charging a 20 kWh battery in less than half an hour. This scenario is also considered that all EV in the parking can be charged at this rate.

Mixed Charging (MC)

In this option 40% of the station are RC charging mode, 20% of them are AC charging mode and 40% of the rest are NC charging mode.

Case B: Distribution Network Substation

For the distribution system operators (DSO) managing the load is a major issue specially when there is local RES production at their network. The presence of EV load is also important as their simultaneous charging load can cause major problem for the grid. In this study we have focused on a distribution substation in the range of 90/20-15 kV with 36 MVA transformers. This grid has also distributed wind productions, which motivates to use its production locally. With rate of EV production in France, it is supposed for this grid to serve near 1300 EVs for the year 2020. The uncontrolled charging profile of this fleet will be analysed where all the EVs have been considered as Normal charging mode arrived around 8:00 at office parking and ask for charging instantaneously. Their departure time is also around 17:00.

CONTRIBUTION OF ELECTRIC VEHICLES

Statistical studies show that in majority of the world cities, the vehicles which are used for daily home/work trips are parked and unused near to 95% of the daily time. This brings high potential for EVs to provide ancillary services for the electrical grid [7]. Reference [7] concludes that the peak power shaving service can be competitive for EV fleet where the interests cover the majority of stakeholders (e.g. TSO, DSO, energy provider and customers). This action can be implemented either by shifting the charging time of the vehicle to the off-peak hours or using V2G technology for discharging the batteries during peak hours and charging them again at off-peak periods. The impacts of this contribution strategy in contrary with uncontrolled charging scenarios are discussed in the rest of the paper for each case study. For both cases the coordination will be analysed with NC scenario.

Case A: Energy Invoice Minimization

Railway station for its local consumption should pay to energy supplier companies an annual bill corresponding to its consumption. The presence of EV charging stations may lead the energy consumption of the railway station to fluctuate. Here we have developed a charging/discharging management strategy by optimizing the energy bill and controlling the load variation. At first, an optimization problem will find the proper energy distribution to minimize the invoice. Then second optimization problem will determine the charging/discharging time of the EVs to achieve the previously explained objective (Fig .1).

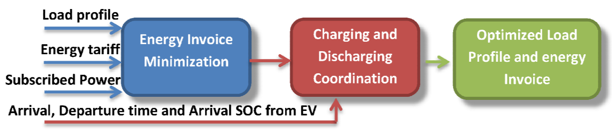

Fig. 1: Optimization process for energy invoice minimization.

Annual energy bill is based on different tariffs of subscribed power. For under studying railway station a tariff fixed by energy supplier company in France (EDF), for users with more than 240 kVA subscribed power is considered. The annual invoice is calculated based on the following equation.

$$Cost = \sum_{j=1}^{5}(d_j E_j) + K.T\sqrt{\sum(\Delta P)^2} + \alpha.P_{sub} \quad (6)$$

Where the first part of second side is related to consumed energy, E_j, in kWh by its price, d_j, in €/kWh for 5 periodical tariffs j. The second part is related to penalty for subscribed power violation (SPV) with T the reduction coefficient related to each tariff interval and the price of kW violation defined by K in €/kW. ΔP is the amplitude of each violation in each 10 minutes average time. Finally, the third part which is a fixed value defined by the subscribed power P_{sub} and base rate value α in €/kW/year. We can now rewrite the Cost function based on load profile to define the best load profile minimizing the cost function:

$$\begin{aligned} Cost = \sum_{j=1}^{5}(d_j \int_{T_j^a}^{T_j^b} LP(t)\ d(t)) \\ + K.T\sqrt{\sum(LP(t) - P_{sub}(t))^2} \\ + \alpha.P_{sub} \end{aligned} \quad (7)$$

The optimum load profile (LP) obtained from this problem will be used in second step as an objective for charging/discharging coordination block. This block aims to minimize the difference between optimum LP and LP which is hosting the EVs by coordinating the appropriate charging/discharging time intervals. The problem is formulated in specific form of Mixed Integer Linear Programming (MILP) so called as Binary Linear Programming (BLP) where the acceptable variable can be just zeros and ones [8].

$$MILP = \begin{cases} min\ c^T x \\ A_{eq}x = b_{eq} \\ A.x \le b \\ x \in \mathbb{Z} \end{cases} \quad (8)$$

$$\begin{cases} EV_{cp}^i(k) = [a_1, a_2, a_3, \dots, a_k] \times C_r^i \\ i = [1, n] \in \mathbb{N}, \quad Number\ of\ EVs \end{cases} \quad (9)$$

$$Cap^i(k) = DLP(k) - LP(k) \quad (10)$$

$$\gamma^i(k) = -|Cap^i(k)| \quad (11)$$

$$\begin{cases} C^i(k) = \gamma^i(k) \times a_k \\ k = [1{,}144] \in \mathbb{N}, 10\,min\,step\ in\ 24\ hours \\ a_k = [0{,}1], \quad binary \end{cases} \quad (12)$$

$$\boldsymbol{Objective}: \quad \min_{a_1,\dots,a_k} \sum_{k=1}^{T} C^i(k) \quad (13)$$

s.t.

$$\sum_{k=1}^{T} A_{eq}.a_k = SOC_{need}^i \quad (14)$$

$$\sum_{k=1}^{T} SOC_{min}^i \le A.a_k \le SOC_{max}^i \quad (15)$$

$$A_{eq} = \frac{Cap^i(k)}{|Cap^i(k)|}, A_{eq} = [-1{,}1] \in \mathbb{Z} \quad (16)$$

As it is shown in the equation the objective is to find the best charging/discharging schedule ($EV_{cp}^i(k)$) which minimizes the cost function. Equation (6) gives the standard formulation of MILP problems. $Cap^i(k)$, is the difference between current daily load profile (DLP) and optimum LP that should be fulfilled by EV charging schedule. To prevent trivial answer of all zeros for a_k, the coefficient of objective function will be introduced in form of $\gamma^i(k)$ function. The vector A_{eq} also defines at which time step the vehicles can be charged (1) and at which one it can be discharged (-1). The constraints of the optimization problem are the availability of the vehicles and their desire SOC at departure time. To prevent excessive negative impacts of battery cycle life in V2G mode the minimum SOC of 20% is also considered [7]. An example of algorithm output for 10 EVs is depicted in figure below.

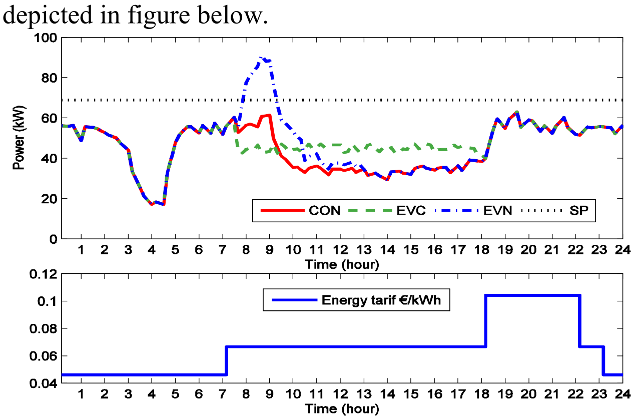

Fig. 2: Upper subplot: Example of a winter day showing charging/discharging coordination, Lower subplot: energy tariff.

The consumption load profile without EVs (CON) is compared with uncontrolled NC scenario (EVN) and coordinated algorithm (EVC). It shows that the algorithm is able to allocate the EVs load in somehow that the Subscribe Power (SP) violation is avoided, load variation is reduced and energy is consumed at lower cost periods. The process for set of different number of EVs has been evaluated where the results are brought in Table I and II.

Table I
Comparison of yearly energy invoice (k€)

Scenario	10 EV	20 EV	30 EV	40 EV	50 EV
CON	22.31	22.31	22.31	22.31	22.31
EVC	23.39	25.34	26	28.8	30.25
EVN	24.97	30.95	34.15	41.95	46.08
Benefit	6.32%	18.12%	23.86%	31.34%	34.35%

Table II
Comparison of yearly SPV indicator (k€)

Scenario	10 EV	20 EV	30 EV	40 EV	50 EV
CON	0.22	0.22	0.22	0.22	0.22
EVC	0.19	0.45	0.59	1.43	2.04
EVN	1.77	6.06	8.74	14.58	17.87
Benefit	89.26%	92.57%	93.24%	90.19%	88.58%

The results in benefit rows are the percentage of each invoice reduction thanks to using coordinated algorithm. The point is that these benefits in sense of SPV indicator are very important. Also for energy invoice, increased number of EVs leads to more benefit percentage.

The results of different uncontrolled charging scenarios explained in previous section (NC, MC, A.C and RC) and coordinated strategy are compared using SPV indicator in function of different number of EVs. These results are depicted in Fig. 3. As it is shown, in all of the uncontrolled scenarios the SPV is increased linearly as the number of EVs is increased. While in coordinated scenario (EVC), the SPV factor has small rate of increment and this leads to serving higher number of EVs without excessive impact on energy invoice by minimizing the range of SPV.

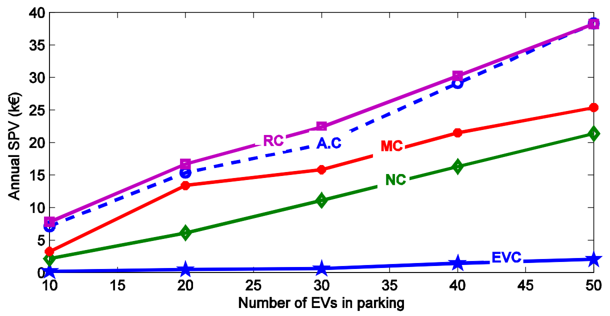

Fig. 3: Different scenario impacts on SPV indicator.

Case B: Energy Transmission Cost Minimization

The distribution grid system operators have to pay the transmission system operators (TSO) a yearly bill related to energy transmission which is called energy transmission cost (ETC). This invoice has several different components, where two of them are more interesting in term of energy management objective [9]. These components are energy absorption (EA) and subscribed power violation (SPV) with a fix part. In order to minimize ETC Invoice, the electric vehicle fleet can have interesting contribution through following means of actions;

- Charging during the low cost energy price.
- Charging during the surplus of RES production.
- Discharging during the high cost energy price.
- Discharging during the surplus of consumption compared to RES in high cost intervals.

ETC is calculated based on tariffs defined by TSO which is called TURPE [10]. To have it minimized, the same problematic as previous case study is taken into account with constraints of EVs availability, battery SOC limitation, RES intermittency, energy tariff and subscribed power limit. This optimization problem is solved using interior point method for its nonlinear objective function. The results for some sample days are depicted in following figures.

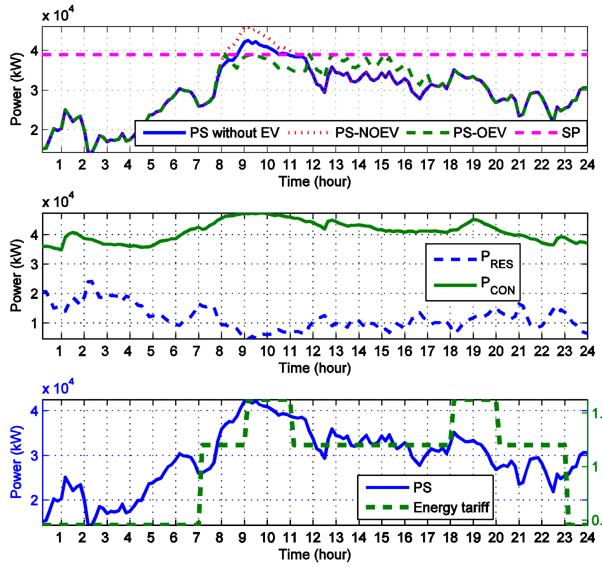

Fig. 4: Example of SPV avoidance and low price energy consumption.

In Fig. 4, three scenarios have been presented at upper subplot. The "**PS without EV**" is the base scenario where it comes from difference between consumption and local RES. This is the power measured at distribution substation entrance so called as **PS** point and shows how much power is absorbed or injected to the grid. PS-NOEV is the scenario of uncontrolled charging abbreviated from **N**on **O**ptimized **EV** and finally PS-OEV which is the **O**ptimized **EV** scenario. As it is shown in PS-NOEV the vehicles are charged at their arrival time to the office parking. While in PS-OEV the EVs are not charged to avoid extra SPV and additionally they are discharged because of high cost energy period between 9:00 and 11:00. Instead, they are charged during lower price interval before departure time around 17:00 [9]. In the other example, which is brought in Fig. 5, the vehicles are charged during surplus of RES production to reduce energy absorption from the grid.

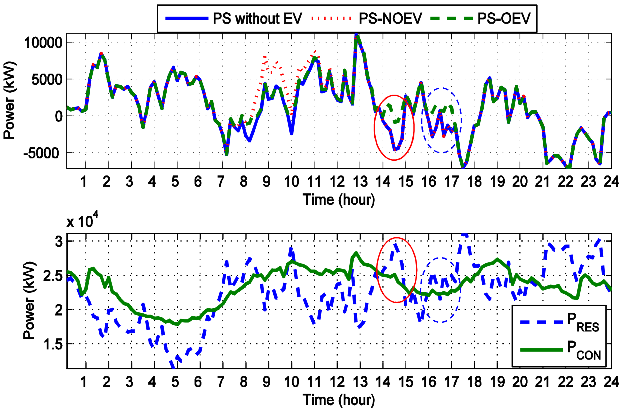

Fig. 5: Example of RES surplus consumption by EVs.

Table III
Comparison of ETC components (k€)

Scenario	SPV	EA	Fix	Total
PS	15.18	886.69	567.46	1469.3
PSNOEV	42.82	910.34	567.46	1520.6
PSOEV	9.81	906.32	567.46	1483.6
Benefit	77.09%	0.44%	-	2.43%
V2G	37.98%	0.44%	-	-

The results of yearly analysis for different ETC components are brought in Table III. These results show interesting contribution especially for SPV component compared to both scenarios. V2G row in Table III shows the contribution of EV fleet thanks to V2G technology for SPV and EA components. In fact by using V2G mode, the EVs can reduce the possible SPV caused by conventional load and bring 37.98% benefit over SPV component. Also for EA components thanks to the V2G some part of load profile in high cost energy intervals can be transferred to lower cost interval. This brings 0.44% reduction for EA component.

CONCLUSION

The impacts and contribution of electric vehicles on the distribution grid and railway station parking lots have been assessed. Different uncontrolled charging modes with coordinated charging/discharging strategy have been compared. For railway stations serving EV charging infrastructure, the presence of energy management system leads to increase number of EVs that can be hosted by parking. In addition the annual energy invoice paid by station can be reduced up to 6.32% for case of 10 EVs. Also the more EVs are served the more the benefit is important. For distribution grid with RES production coordination strategy can provide ETC minimization. In addition V2G storage capacity can provide subscribed power optimization and absorbed energy price reduction. As a perspective of the work the concentration will be on V2G constraints related to battery discharging constraints to find an appropriate point between both grid utilities and EV owners' benefits. In addition the efforts will be on designing a real-time based supervision strategy that can bring benefits near to the obtained optimized results.

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