Agent-based modelling for designing an EV charging distribution systems: a case study in Salvador of Bahia

Jose Evora and Jose Juan Hernandez
University Institute of Intelligent Systems and Numerical Applications in the Engineering (SIANI)
Edificio central del Parque Científico-Tecnológico, Campus Universitario de Tafira, 35017
Las Palmas de Gran Canaria, Spain
jose.evora@siani.es, josejuanhernandez@siani.es

Daniel Barbosa and Paulo Nazareno Maia Sampaio
Salvador University (UNIFACS)
Alameda das Espatódeas, 915, 3rd floor
Caminho das Árvores
Salvador, Bahia, Brazil
daniel.barbosa@pro.unifacs.br,
pnms.funchal@gmail.com

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ABSTRACT

The need to reduce the dependence on fossil fuels has promoted the introduction of new paradigms to improve overall power grid efficiency. Because of this, electrical vehicles are becoming more popular. Notwithstanding, their introduction means new challenges which must be addressed in order that future power grids can support their recharge. To this end, new power grid control mechanisms are being developed to avoid huge expenditures in extending the supply capacity of power grids. Amongst these, one of the most popular is known as "Demand Side Management". The challenge of studying prospective scenarios in which electrical vehicle charging is controlled by a Demand Side Management policy is addressed in this paper. This paper proposes an agent-based modelling approach to deal with this kind of study and presents two experiments in which its advantages are highlighted.

Introduction

The increasing global concern over environmental issues and the need to reduce the dependence on fossil fuels have motivated the proposal and development of new technologies as alternatives for transportation systems. One of the current alternatives presented in literature aimed at automotive manufacturers is the use of electric vehicles (EVs). However, the benefits of this alternative are also questionable, in particular, when it comes to environmental issues and their impact on electrical power systems infrastructure.

According to Putrus et al. (2009), EVs may be considered as active loads since they increase the demand over the power grid during charging and regeneration (when they operate as generators). Therefore, the massive deployment of EVs in the future can impact the power grid's capacity, availability and reliability. Therefore, resultant impact can be helpful in order to determine design requirements of EV's power system interface as well as the layout and control of electrical power systems.

Several studies Papadopoulos et al. (2012), Zhou et al. (2013), Pillai and Bak-Jensen (2010), Putrus et al. (2009), Richardson et al. (2010), Clement-Nyns et al. (2009), Clement et al. (2008) have shown that significant EV penetration can cause disturbances in the distribution power system: thermal loadings of distribution transformers and cables, worsening of the power quality, higher power line losses and promotion of stability problems.

In order to prevent these undesired problems, the research presented in Villafafila-Robles et al. (2013), Tie et al. (2014), Vrazic et al. (2014), Sagosen and Molinas (2013), Callon (1980), Andersson et al. (2010) assess different scenarios in various contexts using case studies in Spain, Malaysia, Croatia, Norway, France, Germany, among others. Although these papers address these issues with different specific goals, in general they address the impact of electric vehicle penetration on electric power system, estimate the number of vehicles in different scenarios and check the regulatory aspects needed to promote the utilization of electric vehicles.

This paper addresses a feasibility study for the deployment of EVs in Salvador, Bahia, Brazil. Salvador is the third-largest urban agglomeration on the northeast coast of Brazil and with a population estimated around 2,883,682 by IBGE Fundação Instituto Brasileiro de Geografia e Estatística IBGE (2010). The power grid supplies public needs within the parameters required by the Brazilian regulatory agency Lamin et al. (2010). The electric supply capacity within a particular region normally exceeds demand levels. As a result, infrastructures are over-sized in order to deal with changes in demand growth and time lags in investment. For these reasons, the electricity industry has reserved power capacity in order to maintain reliability. These reserves typically range from 14%-17%.

The increase of population and the introduction of EVs are important contingencies that must be studied, since

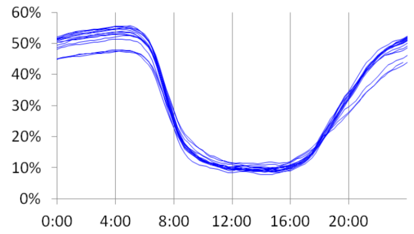

Figure 1: Weekday time-of-day EV charging station usage in Schey et al. (2012)

they will significantly increase the demand for electricity on the grid. Since expenses related to the Brazilian power distribution system need to be reduced, it would be highly desirable that new investments in infrastructure be carefully considered. The challenge consists on extending the operational usage of these infrastructures beyond 2030. One possible solution for the deployment of EVs could be the optimization of power consumption through the utilization of the available capacity in off-peak hours (valleys) instead of increasing the distribution capacity of power grid to supply higher demand peaks.

The main goal of this paper is the validation of a modelling approach using real data related to consumption and prospective studies of EV introduction in Salvador in the coming years. This modelling approach is based on the complex system paradigm when it is required to analyse load-shifting strategies on specific vehicles, depending on the grid state and user needs.

Electric Vehicles recharging

EVs will alter power consumption curves. With the current EV technology, a typical round-trip to work (50 km/day) is equivalent to the daily load of an average home (10 kWh). An example of how EVs are charged is studied in in a pilot project Schey et al. (2012) in Fig. 1. According to this project, more than 30% of charging stations are used between 5:00 PM and 5:00 AM. Since the peak demand in many power grids in between 5:00 PM and 10:00 PM, the charging of EVs could cause problems for power grid regulatory indicators.

However, the policy of EV charging is a significant issue to be addressed, as it could mitigate the need for new investments in power grid capacity. That is because vehicle recharging times could be shifted in order not to exceed the capacity. Demand Side Management (DSM), such as load shifting, demand response, energy storage, retail markets are emerging paradigms for the operation of power grids to flatten the demand Chassin et al. (2014). For example, vehicles could respond to real-time pricing (RTP), in order to reduce peak demand to some degree Hammerstrom et al. (2007). Specifying the maximum price for recharging vehicles would define their recharging behaviour.

Modelling hypothesis

The design of EV charging distribution systems require simulation tools that integrate models of different natures: vehicle ownership, vehicle-kilometres driven, vehicle charging, battery storage and market simulators. In this work, it is validated that an agent-based modelling approach allows the integration of all these models to assess the impact of EVs on the power grid. The simulation tool used is Tafat Evora et al. (2013).

This modelling approach has been used in several studies related to DSM on EV Karfopoulos and Hatziargyriou (2013), Kamboj et al. (2011), Vandael et al. (2010). However, since these kind of models are affected by the available data, the nature of models is not exactly the same. The more data is available, the more complete the model will be.

This model represents every single entity individually: vehicles, district consumption, batteries, drivers, charging stations, substations, feeders and grid operator. Since several agents are working pursuing their own goals, perceiving and reacting to their environment, this modelling approach allows discussion of the design and implementation of a power grid from the point of view of a complex system Pipattanasomporn et al. (2009).

Classical power grid simulations focused in the study of the production scheduling considering the demand as an aggregated load. Some EVs impact studies also consider the introduction of these devices as an aggregated load whose consumption is calculated based on statistics. However, the evaluation of DSM policies requires the disaggregation of the consuming devices so that the way in which the policy affects each individual device can be analysed.

The agent-based modelling approach approach will allow the evaluation of charging policies on a low level scale and also consider potential coupling effects. Moreover, this modelling approach is able to represent heterogeneity since not all the agents make the same decisions and have the same behaviour.

In order to show the advantages of using this modelling approach, two experiments have been performed: the first one shows this impact in the case of recharging EVs without a DSM policy; the second one shows a simple DSM policy based on RTP.

Model development

The development of this model has required to use data of different natures. The next paragraphs below summarise the data that has been used and its justification.

Demography. Current number of inhabitants in Salvador of Bahia and its projection until 2030 (IBGE-Fundação Instituto Brasileiro de Geografia e Estatística IBGE (2010)). This is relevant information for calibrating the original consumption load curve and calculate the number of vehicles.

Vehicle ownership. This is a future projection from now until 2030, calculating the number of vehicles per 1,000 inhabitants. In Dargay et al. (2007), this projection is estimated for many countries, including Brazil.
Electrical Vehicle penetration. This projection provides the ratio of vehicles that is foreseen to be in coming years. In Sullivan et al. (2009), the author provides some penetration rates concerning whether public institutions fund the purchase of electrical vehicles or not. In our model, we decided to take the average of all the scenarios the author proposes. It must be noted that the objective of this paper is not predicting the number of EVs in Bahia, but analysing their impact.
Vehicle usage. This is an statistical data concerns the number of kilometres that are driven by the inhabitants in Salvador of Bahia from IBGEFundação Instituto Brasileiro de Geografia e Estatística IBGE (2010).
Consumption. This information concerns historical data for electrical power that is consumed in a portion of Salvador of Bahia City serving approximately 142,000 inhabitants. This information will be used to compare the impact that the EVs will have when they are massively introduced into the power grid.
Due to the difficulty in obtaining complete information from the electrical company, this study uses data from one typical district in Salvador with residential, commercial and industrial sectors, including schools and faculties, malls, etc. The substation in this district consists of two 69kV/11.9 kV and 20 MVA three phase power transformers in operation and 10 distribution feeders that it supplies 58,308 consumer units in low and medium voltages.
Since the predicted penetration of EVs from 2014 to 2029 is not significant, the model has been made for a prospective scenario in 2030. Using the predictive studies, the EV fleet has been sized for the modelled district in 2030. According to the prospective studies in Sullivan et al. (2009), the penetration rate of EVs in 2030 is about 10.4% when averaging the most optimistic and pessimistic perspectives. For the population of the portion under study, this means 5,253 vehicles. For each of these vehicles, an agent and a charging station are attached.

Electric Vehicle and Driver Modelling

The EVs have been modelled to represent any EV in the market. It is easily parameterised by simply providing the battery capacity (in kWh), the autonomy (in km) and the starting state of charge (from 0% to 100%). In this simulation, vehicles in table have been taken into account.
These vehicles are discharged based on the mileage they cover. This means that the energy that has to be discharged from the battery is calculated based on the kilometres that have been driven and the autonomy of the vehicle. Vehicles are charged according to the standard

Brand	**Model**	**Capacity**	**Range**
Mega	e-City	9kWh	100km
Reva	L-Ion	11kWh	120km
Think	City	25kWh	200km
Mitsubishi	i-Miev	16kWh	130km
Citroen	C-Zero	16kWh	130km
Renault	Fluence-ZE	22kWh	160km
Nissan	Leaf	24kWh	160km
Tesla	Roadster 42	42kWh	257km
Tesla	Roadster 70	70kWh	483km

which is at 3,700 watts.
This electrical vehicle model needs to be commanded by an agent model in order to perform the trips (e.g. going to work). Therefore, an agent has been developed to implement the behaviour of the driver who needs transportation. This agent has been implemented in accordance to ordinary lifestyles, since it was not possible to obtain information of usage patterns for vehicles. These agents execute four activities which concern the use of the vehicle: going to work, returning from work, going to shops, returning from shops. An example of how these agents are scheduled is presented below:

- Activity 1. Id: go work. Time: 7:00. Deviation: 500s. Pattern: Monday, Tuesday, Wednesday, Thursday, Friday.
- Activity 2. Id: back from work. Time: 15:00. Deviation: 500s. Pattern: Monday, Tuesday, Wednesday, Thursday, Friday.
- Activity 3. Id: go shop. Time: 18:00. Deviation: 500s. Pattern: Tuesday, Thursday, Sunday.
- Activity 4. Id: back from shop. Time: 21:00. Deviation: 500s. Pattern: Tuesday, Thursday, Sunday.

In addition to this information, agents are also provided with the distance to work and to the shops. These distances are calculated based on a normal distribution centred in the average mileage driven by people in Salvador de Bahia. After each activity, the agents will plug in the EVs so that they can start charging their batteries. However, depending on the strategy, the connection of the vehicles to the grid will not necessarily involve its charging, as this will be decided by the strategy. This means that in the simulation in which there is not a strategy, EVs will start to charge as soon as they are plugged in. In the simulation in which there is a strategy, EV charging will start in accordance to the policies of the strategy.

Experiments

Keeping the same distribution infrastructures, the charging potential of the substation for electrical vehicles can be defined as the difference between the maximum deliverable power to vehicles connected to charging stations and the current energy demand: $Pp(t) =$

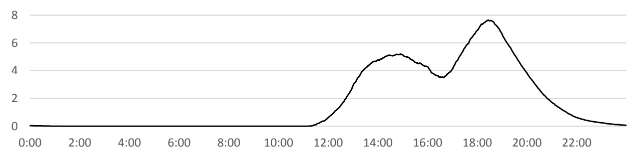

Figure 2: EVs consumption when they start charging as soon as they are plugged

$Pm(t) - Pd(t)$. Obviously, this potential is not the same in all power grid substations, since both factors, Pm and Pd, may vary from one substation to another as well as seasonally.

In the proposed charging model that this paper explores, one or more substation feeders will be enabled to allow the management of all vehicles based on these two factors. Ideally, the energy used for their charging should be the cheapest. Moreover, system operation should be facilitated so that generators are switched on and off as little as possible. To this end, the objective should pursue the flattening of the demand curve.

No DSM policy

In this experiment, the model previously presented will be simulated considering that EVs start charging as soon as they are plugged in. In the figure 2, the consumption of EVs for a weekday is presented. The highest peak of this load curve can be found at 7pm approximately. This peak is due to the fact that almost everyone is at home at this time, with their EV plugged in, with the result that that their charging reaches the greatest level of overlapping. This overlapping effect is also high in the morning and afternoon, coinciding with commuter "rush hours".

In the figure 3, two load curves are presented: the original load curve for 2014 (grey) and for 2030 in which EVs are included (black). In this chart, it can be seen the increment that involves the EVs in the total consumption. As a remainder, this significant impact is caused by 5,253 EVs in a power grid serving an area of 142,000 (in 2014) and 149,000 (predicted for 2030) inhabitants. If any of the three predictions that are used in this study increases (population, vehicle ownership rate or EVs penetration rate), would result in the consumption increment being higher. It can be observed that the impact of introducing 5,253 EVs can reach 8 MW, which is significant considering that the maximum consumption of this area for the analysed day is 103 MW. This approximately means an 8% increment. Along with this increment, we must also consider how the rest of the energy demand not provoked by the EVs introduction has increased as well. This leads to a total increment of approximately 15MW. This would mean that this substation would have to be re-sized.

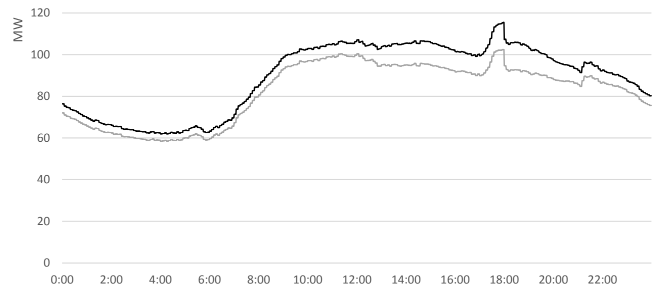

Figure 3: Comparison of the original load curve for 2014 (grey) with the total consumption including EVs charging for 2030 (black)

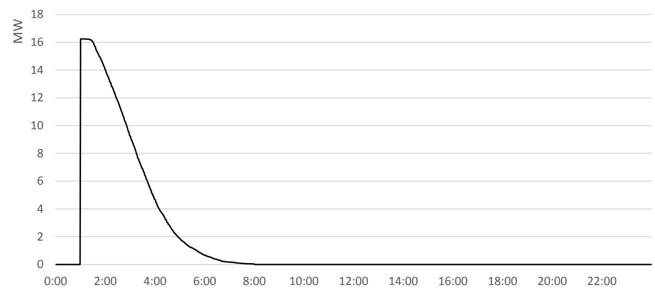

Figure 4: EVs consumption according to the RTP based policy which makes cheaper charging from 1am to 8am

RTP-based DSM policy

Knowing the valley existent in the early morning, RTP policy has been programmed to output a very cheap price for the energy that is consumed from 1am to 8am. In these experiments, all vehicles have been tuned to only accept this price. In the figure 4, the consumption of the EVs is presented under this new policy. As it can be observed, since many vehicles have not been charged during the previous days, most of them start charging their batteries at 1am, thus producing a high demand peak of 16MW. This consumption becomes 0 at 7am approximately.

In the figure 5, again, two load curves are presented: the original load curve for 2014 (grey) and for 2030 in which EVs are included (black). This time, the peak that already existed in the load curve for 2014 has only increased as consequence of the population increase for 2030. This time, EV charging has been shifted to an off-peak period which is in the early morning. In this new interval, EVs charging does not increase at all the overall maximum peak of the demand allowing for a greater introduction of EVs if it was necessary. Notwithstanding, there is an abrupt increase of the consumption at 1am since almost all EVs start charging at that time due to the low prices. This is a non-desired effect for the grid stability and should be further studied in order to smooth their charging starting process.

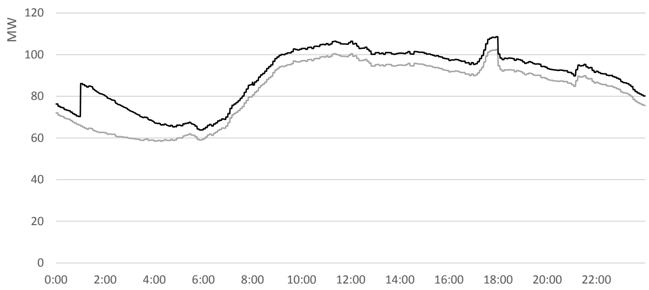

Figure 5: Comparison between original load curve for 2014 (grey) with the total consumption including EVs charging (black) using the RTP-based policy for 2030

Conclusions and outlook

This work has been oriented to develop the model of Salvador of Bahias power grid using an Agent-based modelling approach. This work has allowed to validate the ability of this modelling approach to:

1. Model individual decision making.
2. Consider local constraints.
3. Model power grids as social technical system.
4. Study emergent synchronisation and coupling effects when many agents coincide.

The major advantage is that this model is able to simulate human decisions and actions that would affect the functioning of the power grid. In addition, such changes in the grid would in turn influence human decisions and actions. Once this model is developed, future projects will be oriented to design and assess DSM policies that would help reduce investments on grid infrastructure. On the other hand, the agent decision model could also be improved. For example, agents could make decisions based on responses to changes in the system, which will in turn change the context for future decisions; or agents could behave in a heterogeneous way, thus maximising a certain profit, either a full charging of the vehicle or save money.

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