Simulation and Design of a Fast Charging Battery Station in a Parking Lot of an e-Carsharing System

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***Abstract*—Carsharing has the potential to reduce the total number of cars on the road, with significant benefits to the society and the environment, while at the same time relevant studies show that university communities are often more receptive to alternative transportation services compared to the general population. With the growing interest in electromobility, as a means of decarbonizing the transportation sector, this paper considers the case of combining carsharing with electric vehicles (EVs) to serve the commuting needs of students, employees and faculty of a university in Bilbao, Spain. The aim of the present work is to conceptualize the design of the charging infrastructure of the e-carsharing system under a fast charging scheme and define its components, their attributes and interactions. To this end, a MATLAB/Simulink based simulator is developed incorporating the dynamics of a real-world scenario based on arrival and departure data from the university parking lot.**

Keywords—electric vehicle; car sharing; university; charging post; battery; simulation

I. INTRODUCTION

Admittedly, the increasing human needs for mobility combined with the use of private vehicles are primary causes of serious environmental and social problems worldwide, having a negative impact on the quality of life [1-2]. The high use of private cars is known to be a source of high levels of air and noise pollution, as well as parking and traffic congestion problems, mainly in urban areas [2-3]. Relevant studies indicate that conditions of traffic congestion are typically observed at peak hours when people commute to work [4-5]. In this context, carsharing serves as a substitute for private car ownership that has also positive contribution to urban mobility, mainly because the shared cars are used more efficiently [6-8], while reducing at the same time the total number of cars on the road [9-11]. In this direction, university administrations and members are often considered to be more receptive to alternative transportation services such as carsharing [12], compared to the general population [13].

The present paper considers the case of providing carsharing services with electric vehicles (EVs) in a university setting to serve the mobility needs of students, employees and faculty from their residential point to the campus. In particular, the focus is on the design of the charging infrastructure to support the effective operation of the e-carsharing system under a fast charging scheme. To this end, a MATLAB/Simulink model is developed for properly dimensioning the electronic components of the charging station to meet the energy requirements of a fleet of 8 EVs.

II. DESCRIPTION OF E-CARSHARING SYSTEM

In the frame of this work, it is considered that the base of the envisaged e-carsharing system is a parking lot at the university campus with an EV station with fast charging capabilities (Fig. 1), while there are 7 parking spots (A-G) around the city of Bilbao, Spain, where the users can pick-up and drop-off the EVs in order to commute to the university. Moreover, the characteristics of the Nissan LEAF 2011 model in [14] are employed in order to estimate the energy consumption of a trip. Although the specific EV is equipped with a lithium-ion battery rated at 24 kWh, it is further assumed that the usable battery capacity C_{batEV} is 21 kWh (57.6 Ah), resulting in a range R_{EV} of 116.8 km per complete charge. When the user makes a reservation for an EV, the system must ensure that the state of charge (SOC) of the EV battery is sufficient to complete a roundtrip, i.e. it can reach its destination and return in a single charge. To this end, the minimum requirements in terms of energy stored in the EV battery $E_{batrndtrip}$ to complete a trip are expressed in (1), where D is the roundtrip distance. Specifically, the calculations take into account the energy consumption of the trip, incremented by 10% of battery capacity as a safety factor and by 15% of battery capacity that represents the low charge zone of the battery, which should not be reached in order to preserve the battery's life expectancy. Table I shows the corresponding minimum battery energy and SOC requirements for each roundtrip to the 7 pick-up/drop-off points A-G, having the university campus as starting point [15].

$$E_{batrndtrip} = C_{batEV} * \left(D / R_{EV} + 10/100 + 15/100 \right). \quad (1)$$

A. Datasets of Parking Lot Occupancy

To analyze the parking behavior of the potential users, two sources of data are examined: (i) a dataset provided by the university services covering three parking lots for nearly a 1-year period, and (ii) a dataset collected and processed from an experiment performed at a specific parking lot of the university campus (as a potential location of installing the EV charging station), where a team of participants recorded the parking spot (place) and time of cars over the course of a day, including both weekdays and weekends. The first dataset (obtained from the university services) regarding the entrance and exit of cars during a 12-month period is compared with the data of the field experiment in order to examine whether the latter is a good representation of an average day or not. The purpose is to use the data from the experiment if possible, as it comprises exact recordings from the parking lot, whereas the data provided by the university had some flaws resulting from the non exact recording of the arrivals or departures of the cars. Specifically, the data provided by the university had to be filtered for consistency, since the original raw data contained entries of cars without a registered entrance or exit, e.g. due to failure of the gate or they were moving behind another car that opened the gate. Thus, these entries were excluded from further analysis, given that no useful information could be extracted about the parking duration.

B. Distribution of Car Parking Duration

The data of the car parking duration provide useful insight on whether there will be enough time to charge the EV battery of a potential user of the e-carsharing system using the fast charging option. Indicatively, Figs. 2 and 3 present the car arrivals and departures respectively during a day according to the field experiment, while Fig. 4 shows the distribution of average parking durations on Mondays based on the yearly data. The analysis of the available data revealed that the commuters using a car follow a similar pattern during the weekdays, except for the case of Fridays, where the frequency of short duration parking (up to 30 min) is roughly doubled. The similarity (in terms of correlation) of the available data from the two sources indicates that those collected from the field experiment can be used as a good average estimate of those provided by the university for the 1-year period. The data of arrivals, parking duration and departure comprise the basis for representing the behavior of the potential users of the e-carsharing system in the simulation model developed for properly dimensioning the components of the EV charging station.

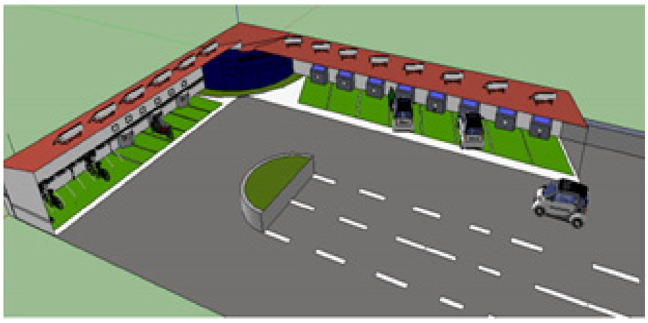

Fig. 1. The envisaged fast charging station of the e-carsharing system.

TABLE I. MINIMUM BATTERY ENERGY AND SOC REQUIREMENTS FOR ROUNDTRIPS FROM UNIVERSITY CAMPUS TO DESTINATION POINTS

Destination point	***D* (km)**	**Minimum battery energy (kWh)**	**Minimum SOC (%)**
A	23.0	9.39	44.69
B	24.0	9.57	45.55
C	29.6	10.57	50.34
D	19.4	8.74	41.61
E	5.6	6.26	29.79
F	8.0	6.69	31.85
G	5.2	6.18	29.45

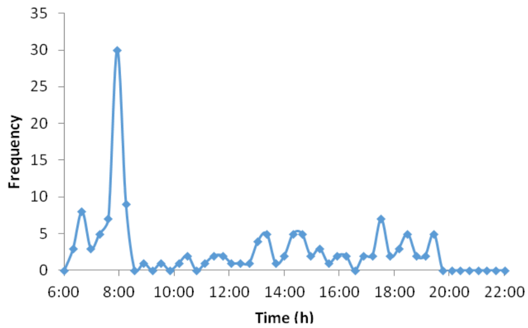

Fig. 2. Car arrivals during a day according to the field experiment.

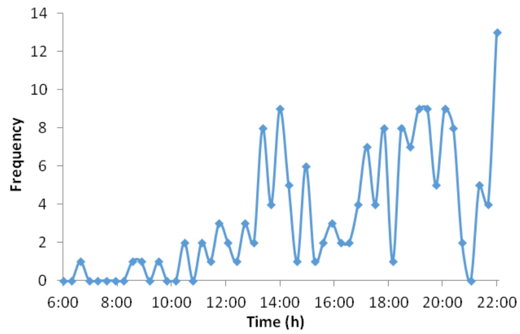

Fig. 3. Car departures during a day according to the field experiment.

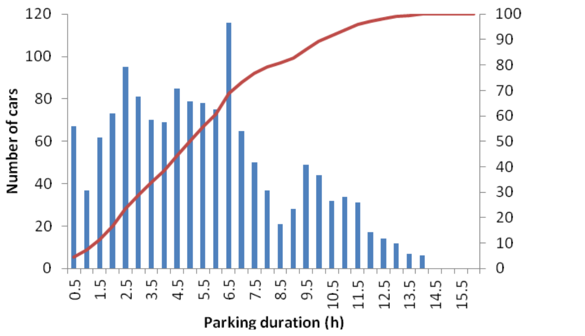

Fig. 4. Average parking duration on Mondays according to the filtered university data.

III. Charging Circuit Design

The electronic circuit of the EV charging station includes a full wave rectifier and a boost converter in order to charge its battery at the proper voltage and current. The focus is on calculating the design parameters of these components to provide the required electricity to each charging post (of the EV charging station), starting from the rectifier and then proceeding with the electronic elements of the boost converter. It is noted though that the efficiency of this part of the system is out of the scope of the present paper.

A. Rectifier

The battery of a charging post is considered to be charged during the nighttime from the grid, when the electricity price is lower, and be used during the daytime to charge the EV batteries. A practical and efficient way to transform the three-phase electrical (AC) input into a usable state for the system (DC) is by using a three-phase bridge rectifier consisting of 6 diodes, as shown in Fig. 5.

B. Boost Converter

The role of the boost converter is to step up the voltage to the required value, being the output voltage higher than the input voltage (Fig. 6). In the case of the present work, it is assumed that the battery of a charging post needs a nominal voltage of 420 V to charge the EV battery, while a voltage boost to 483 V is needed to charge the battery of a charging post. Given that the input voltage V_s is 345 V, the output voltage V_a is 483 V, the switching frequency f_s is 10 kHz and the output current I_a is 60 A, the resistance R, the duty cycle k, the critical inductance L_c and the minimum capacitance C_{min} are calculated in (2) to (5) respectively, where ΔV_a is the desired output voltage ripple. The values of the design parameters are selected to meet the application requirements, enabling the charge of a 120 Ah battery in 6 hours, which is sufficient for the case of night charging from the grid.

$$R = \frac{V_a}{I_a}. \quad (2)$$

$$k = 1 - \frac{V_s}{V_a}. \quad (3)$$

$$L_c = \frac{(1-k)^2 * k * R}{2 * f_s}. \quad (4)$$

$$C_{\min} = \frac{I_a * k}{f_s * \Delta V_a}. \quad (5)$$

IV. Control Circuit Design

The battery to battery (B2B) charging simulation includes a control circuit in order to decide whether a charging post should charge an EV arriving to the parking or not, built as a simulation model that combines Simulink logical blocks with MATLAB code (Fig. 7). Based on the current SOC and the destination each EV is heading to, it evaluates the required SOC and decides to charge it, if necessary.

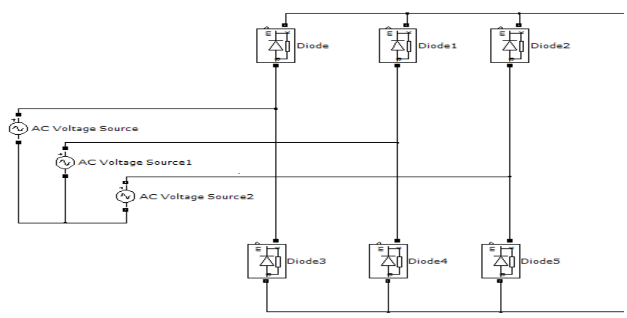

Fig. 5. Three-phase bridge rectifier.

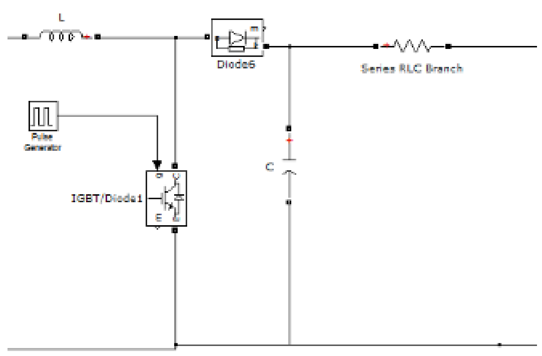

Fig. 6. Boost converter.

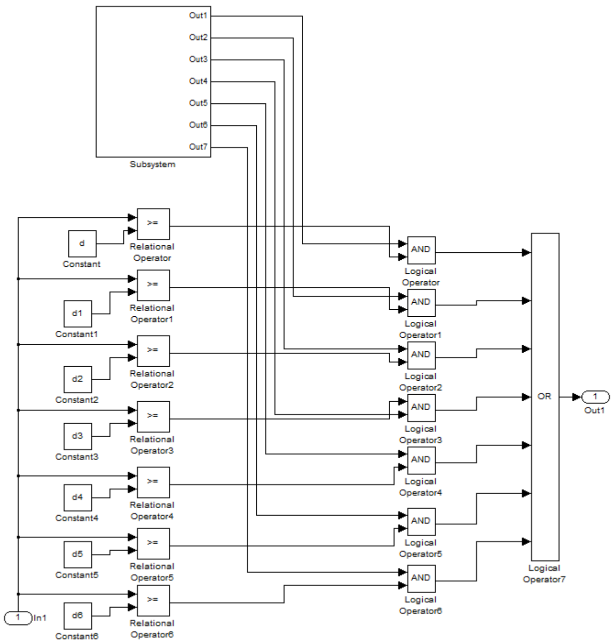

Fig. 7. Control circuit of the charging posts.

Specifically, the daytime is divided into 64 timeslots of 15 min, corresponding to the hours from 6 am to 10 pm. The time step duration was chosen on the basis of enabling fast charging of EVs. The underlying assumptions and steps of the simulation are the following:

1) The initial SOC of each charging post is set to 100% (charged overnight from the grid).
2) The initial SOC of the 8 EVs of the e-carsharing system is generated randomly in the range between 50% and 60%.
3) The arrivals of the EVs are generated according to the probability established by the data from the field experiment.
4) The destinations of the EVs are generated according to the distribution of population living in the surroundings of each one of the 7 destination points A-G, based on the data available in [16-17].
5) The necessary energy to reach the destination is compared with the energy stored in the EV battery and the post initiates the charging process if needed.
6) A while loop repeats the process from step 3 and onwards, until 64 iterations are completed. Then, an evaluation report shows the number of charged EVs, as well as if and when there has been any unsuccessful charging.
7) After the system is run for a time step, the SOC of the charging posts and EVs is evaluated in order to determine if the system behaved properly. An indicator is employed to check whether the charging has been completed successfully or not and determine the efficacy of the system.

Fig. 8 shows that the charging process is controlled by opening or closing the "Ideal Switch1" upon system request, where "Battery2" represents the battery of a charging post and "Battery3" represents an EV battery. The logical blocks in Fig. 7 provide a binary input to indicate whether the system needs to start or stop charging based on the SOC of the EV and the destination generated by the code. The EV destinations are generated with the subsystem in Fig. 9, which comprises a component of the control circuit (Fig. 7).

As a starting point, it is further assumed that the batteries of the charging posts have a capacity of 120 Ah (50.4 kWh) to supply energy to the 8 EVs. Taking also into account that the maximum number of arrivals in a single time step is 22 cars, while the capacity of the parking lot is 65 cars, it follows that $\lceil 22 * 8 / 65 \rceil = 3$ charging posts are required to supply energy to the EV fleet in the worst case scenario.

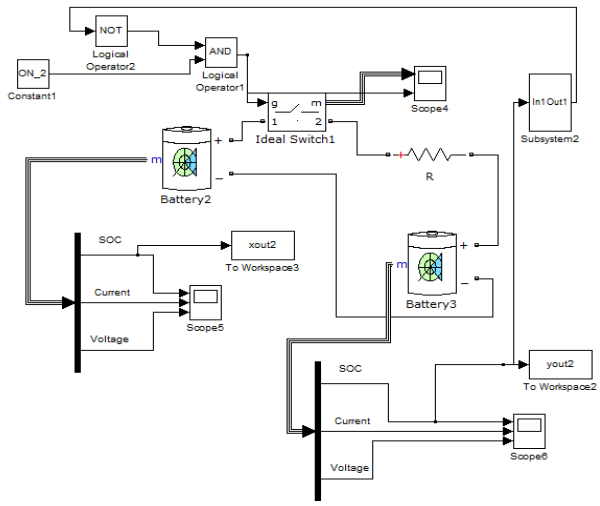

Fig. 8. System for controlling the charging process of the EV battery.

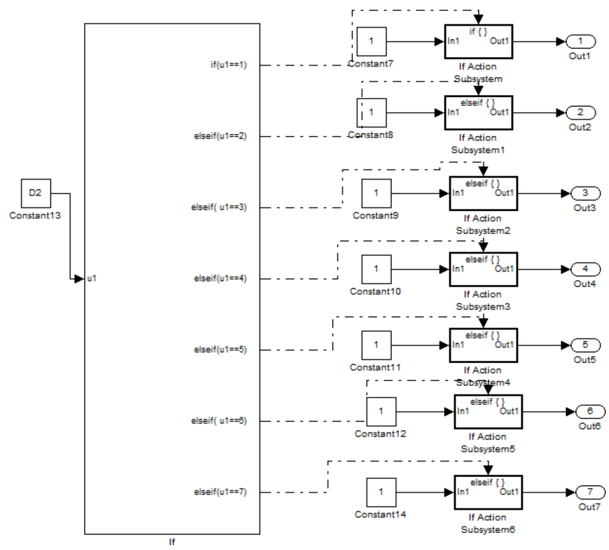

Fig. 9. Subsystem for generating the EV destinations.

V. SIMULATION AND RESULTS

As already pointed out, the simulation model depends on a number of variables that take values from a probability distribution, thus 5 simulation runs are performed to obtain sufficient output results over the working days of a week with respect to the energy needed by the system. The batteries of the charging posts have initially a capacity of 120 Ah (50.4 kWh) and are fully charged at the beginning of each day (charged overnight from the grid). The aim of the simulation is to optimize the capacity of the charging post batteries, while ensuring that the whole system operates effectively. The objective is to achieve a 100% success rate for the proposed EV charging system, i.e. charge the EVs of the e-carsharing system when needed in order to successfully complete their roundtrips. The results obtained for each simulated day are presented in Table II, clearly showing that there is excess of energy remaining at the posts after charging between 20 and 30 EVs. Hence, there is significant margin to reduce the capacity of the charging post batteries, and thus improve the cost of the proposed system. Fig. 10 shows the total amount of energy provided by the three charging posts each weekday.

Although the average energy provided by the three charging posts (47.22 kWh) is a key indicator for determining the optimal size of their battery capacity, a safer solution is to consider the capacity needed in the worst case scenario (58.7 kWh), i.e. day 2 in Fig. 10. Similarly to the case of determining the minimum SOC needed by an EV to complete a roundtrip to each destination point A-G, the total capacity of the charging post batteries C_{total} is determined by taking into account a 10% safety factor and the fact that the battery operation in the low charge zone (below 15% of capacity) can significantly shorten its life expectancy, as follows:

$$C_{\text{total}} = 58.7 * 1.1 / 0.85 = 75.97 \text{ kWh} . \quad (6)$$

It follows that the capacity of the battery in each charging post C_{cpost} is a third of the total capacity calculated for the system:

$$C_{\text{cpost}} = \frac{C_{\text{total}}}{3} = 25.32 \text{ kWh} . \quad (7)$$

TABLE II. REMAINING ENERGY AT THE END OF EACH DAY (INITIAL SIMULATION)

Day	Charging post 1 (%)	Charging post 2 (%)	Charging post 3 (%)
1	78.21	64.31	61.93
2	63.24	61.00	59.30
3	63.92	86.28	79.54
4	62.54	68.69	73.08
5	67.97	66.61	74.89

Having determined the battery capacity of each charging post, another set of 5 simulations is run in order to check the performance of the system in supplying the energy required by the EVs. The results obtained in this case are presented in Table III, while a comparison between the initial and final simulation with respect to the total remaining energy in the charging posts in each day is given Fig. 11. The results confirm that the system successfully covers the energy demand by the EVs and at the same time the charging post batteries operate out of the low charge zone.

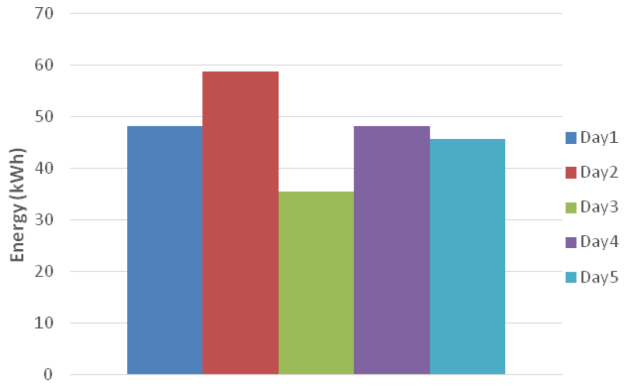

Fig. 10. Total energy provided by the charging posts each day (initial simulation).

TABLE III. REMAINING ENERGY AT THE END OF EACH DAY (FINAL SIMULATION)

Day	Charging post 1 (%)	Charging post 2 (%)	Charging post 3 (%)
1	68.07	18.48	36.58
2	68.86	63.32	50.56
3	40.00	22.83	30.80
4	45.46	54.31	55.74
5	32.46	53.02	62.22

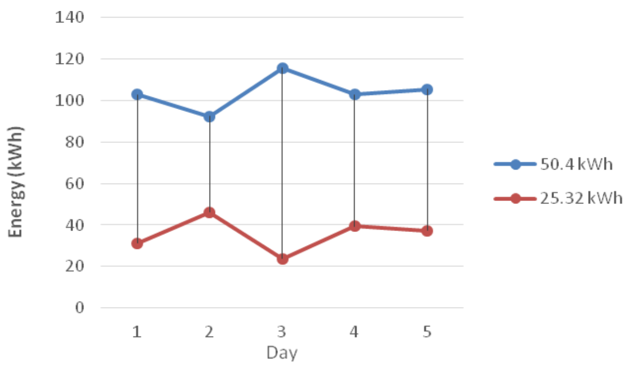

Fig. 11. Total remaining energy in the charging posts in each day between initial (blue) and final (red) simulation.

VI. CONCLUDING REMARK

The present work describes the design of a fast charging station for a university-based e-carsharing system. In this context, a MATLAB/Simulink model is developed to determine the design parameters of the charging infrastructure under realistic conditions. To this end, the system performance is assessed through a number of simulation runs to ensure its effective operation. The results obtained confirm that the proposed system design can effectively support the mobility needs of the target users, taking into account their geographical distribution as well as their behavior in terms of time of arrival, parking duration and time of departure.

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