Electric Vehicle Battery Swapping Stations, Calculating Batteries and Chargers to Satisfy Demand

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Abstract: A high Electric Vehicle (EV) uptake is anticipated in the forthcoming years. Some concerns of vehicle users in switching from conventional internal combustion engine vehicles to Electric Vehicles, relate to distance range anxiety and the time required to recharge the EV batteries. The battery swapping station concept, which consists of replacing depleted batteries for fully charged batteries (in minutes), may incentivise EV adoption by having a similar role to that of petrol stations. In this paper the operation of an EV battery Swapping Station Manager (SSM) is analysed. A methodology is presented to calculate the number of chargers and batteries required to satisfy daily battery demand. The effects of the number of batteries and chargers on the swapping station's electricity load profile are shown.

Key-Words: Electric Vehicle, Battery Swapping Station, Electric Vehicle Battery Charging.

1 Introduction

EV battery charging infrastructures are required to charge Electric Vehicles. The charging infrastructure considered in this paper is the battery swapping station. Battery swapping stations replace depleted batteries for fully charged batteries. Swapping stations are currently being developed and their operation is being tested in field trials [1], [2].

In this paper the operation of an EV battery Swapping Station Manager (SSM) is proposed with the policy of charging the depleted batteries as soon as possible. The operation of a software tool that calculates the batteries and chargers required to satisfy battery daily demand in a swapping station, is analysed.

2 Swapping Station Operation

The Swapping Station Manager (SSM) software manages the charging of the batteries in a battery swapping station, with the aim of providing fully charged batteries to the EVs in exchange for their depleted batteries.

The management of the EV battery charging is dependent on:

- The number of chargers installed in the swapping station.
- The number of batteries in the swapping station. This number remains constant since for every fully charged battery delivered, a depleted battery is acquired.

The batteries in a swapping station can be in three different states:

i) Charging: The battery is connected to a charger.
ii) Fully charged: The battery has finished its charging process and it is available to be swapped.
iii) Depleted: The battery provided by the EV remains in this state until it is placed in a charger. In this research, batteries in this state are referred to as being in the Depleted Battery Queue (DBQ).

The swapping station charging policy is to charge the depleted batteries as soon as possible, ensuring the maximum number of charged batteries at every time interval.

The process followed by the SSM when an EV arrives at the swapping station is shown in Fig.1.

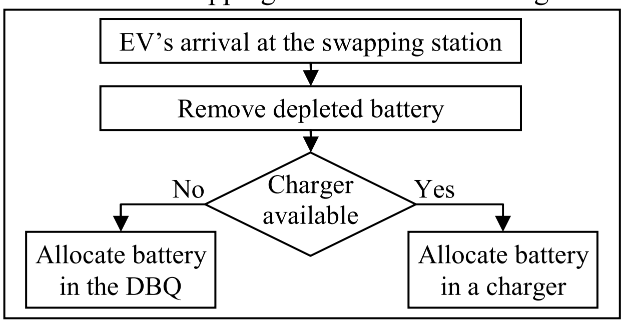

Fig.1 SSM process at an EV's arrival

The process followed by the Swapping Station Manager (SSM) when a battery reaches the fully charged state in a charger is shown in Fig.2.

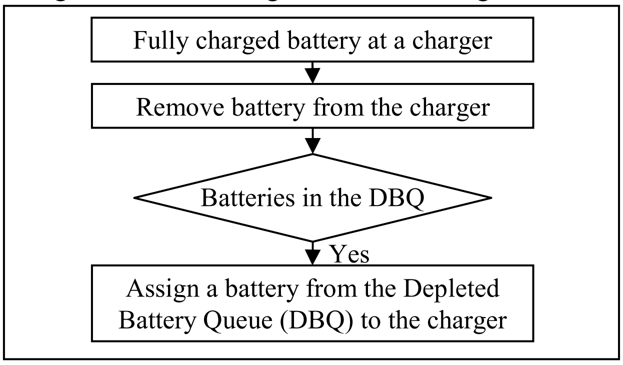

Fig.2 SSM process when a battery reaches fully charged state in a charger

3 Calculation of Required Batteries and Chargers

A JAVA™ based software tool was developed to determine the number of chargers and batteries required to satisfy a given daily battery swap demand (number of batteries swapped per hour).

The number of batteries and chargers required are dependent on the following factors, shown in Table 1, which are also the input data for the SSM software tool.

Table 1. Software tool inputs

Input	Description
Battery demand	Number of batteries swapped at each hour.
EV arrival time within each hour	Time when an EV requests a fully charged battery.
Battery characteristics	Capacity in kWh and efficiency.
Charger characteristics	Power rating in kW and efficiency.
Swap duration	Time, in minutes, required by the swapping station to swap the battery.
Depleted batteries SoC	State of Charge (SoC), in percentage, of the depleted batteries exchanged.
Tool search space	
Number of batteries	Minimum and maximum number of batteries.
Number of chargers	Minimum and maximum number of chargers.

The *EVs' arrival time within each hour* and the *Depleted batteries' SoC* are modelled as a random numbers.

4.1 Computational Procedure

The tool runs a user-defined number of simulations for each combination of chargers and batteries. For each simulation:

- A daily horizon is considered.
- A new set of random data is generated.
- The algorithm records if the battery demand is not satisfied.

The algorithm records that the battery demand is not satisfied if at the arrival time of an EV no batteries are available to be swapped (i.e. fully charged). The computational procedure is shown in the Appendix, Fig.7.

Time intervals of one minute are used for the calculations. For each time interval, the algorithm checks the batteries' state at the chargers. If a battery has become fully charged, the number of available batteries to be swapped increases by one. If there are depleted batteries in the Depleted Battery Queue, a battery is assigned to the charger that became available. This process is shown in the box *batteries' state updating* of Fig.7.

Once the state of all batteries placed in the chargers is examined, the algorithm checks if an EV has arrived at the swapping station. When an EV arrives:

- If there are no fully charged batteries available to be swapped, the event *battery demand not satisfied* is recorded, and a new simulation runs.
- If there are batteries available, the battery delivered to the EV decrements the number of fully charged batteries by one. Thereafter, depending on the chargers' availability, the EV's depleted battery is placed in a charger or in the Depleted Battery Queue.

This process is shown in the box *Process at an EV's arrival* of Fig.7.

For each combination of chargers and batteries, the software tool:

i) Calculates the probability of the battery demand not being satisfied (number of *battery demand not satisfied* events recorded divided by the number of simulations).
ii) From those combinations with a 0% probability of the battery demand not being satisfied, the minimum number of batteries and chargers required are derived.

A schematic of the tool is shown in Fig.3.

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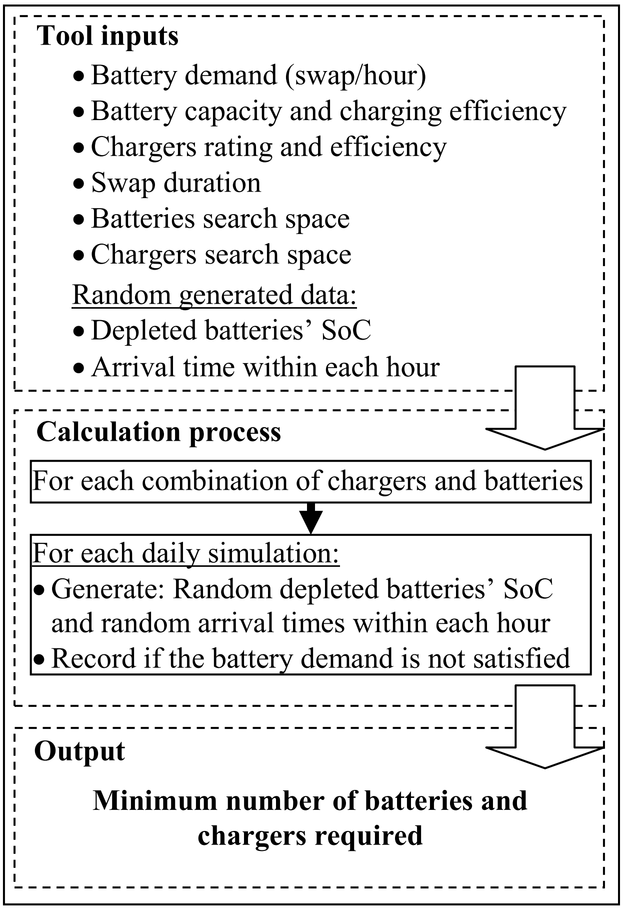

Fig.3 Schematic description of the software tool

4 Case Studies

4.1 Assumptions

The chargers within the swapping station have the same power rating and the same charging efficiency.

The hourly battery demand (number of batteries swapped at each hour) is set according to the utilisation pattern of a petrol station [3]. The time required to swap a battery is considered to be 5 minutes, hence the maximum number of batteries swapped per hour is 12 [3]. Fig.4 shows the hourly battery demand used.

Batteries are modelled as purely resistive loads, charged at constant power rating. All batteries are identical, with the same energy capacity (kWh) and the same charging efficiency. The State of Charge (SoC) of the depleted batteries is modelled as a random number with a normal distribution: mean 20% and a standard deviation of 10%. At the beginning of the day, the batteries in stock at the swapping station are fully charged.

The arrival times of the EVs within each hour are modelled as random numbers with a uniform distribution, with the following constraint: two arrivals cannot occur within the time required to swap the battery. If a car arrives when another EV is swapping its battery, the new EV waits until the swap is finished.

Table 2. Case study assumptions

Battery demand (swap/hour)	Distribution of Fig.4 [3].
Batteries swapped/day	69 [3].
Swap duration	5 minutes [3].
Battery capacity	35kWh [4].
Battery efficiency	85% [5].
Chargers rating	43.64kW (3Φ, 400V, 63A) [6].
Charger efficiencies	87% [7].
Daily simulations	10000.
Batteries search space	1-20.
Chargers search space	1-20.
Randomly generated data	
Arrival time within each hour	Uniform distribution
Depleted batteries' SoC.	Normal distribution. Mean=20%. Standard deviation=10%

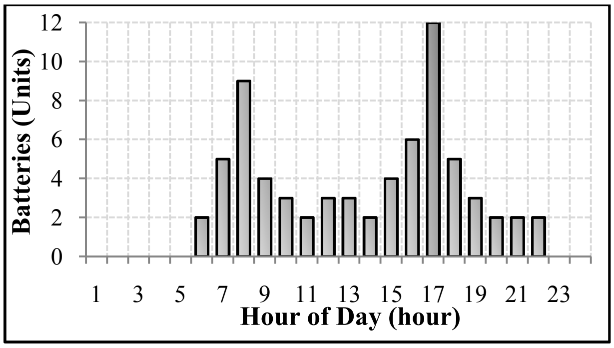

Fig.4 Daily battery demand (adapted from [3])

4.2 Description of the Case Studies

Two case studies were conducted. In Case study 1 the swapping station's minimum number of batteries and chargers are calculated for the assumptions presented in Table 2. In Case study 2, for different combinations of chargers and batteries, the simulated chargers were monitored and the load profile of the swapping station was obtained.

The description of the case studies is provided in Table 3.

Table 3. Description of the case studies

Case	Description
Case study 1 Fig.5, Table 4	The probability of the demand not being satisfied is calculated for all combinations of chargers and batteries investigated (Fig.5). The minimum number of batteries and chargers required to satisfy the daily battery demand, as shown in Table 4, are derived from those combinations with a 0% probability of the battery demand not being satisfied.
Case study 2 Fig.6	Two daily simulations were run and the swapping station's load profiles were plotted. In both simulations the same random data were used, hence the energy consumed by the swapping station was the same. The first daily simulation used the minimum number of batteries obtained in Case study 1 and the second daily simulation used the minimum number of chargers obtained in Case study 1.

4.2 Results of the Case Studies

Fig.5 shows the probability of the battery demand not being satisfied for different combinations of chargers and batteries. The range of chargers and batteries used in Fig.5, shows the minimum number of batteries and chargers required (with a 0% probability of the battery demand not being satisfied).

As the number of chargers increased the minimum number of batteries required was reduced, and conversely.

In Table 4 the minimum number of batteries and chargers required to satisfy the EV daily battery demand are shown.

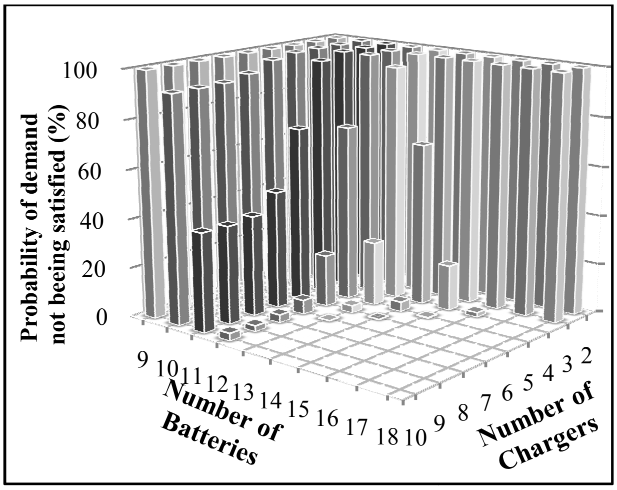

Fig.5 Probability of demand not being satisfied

Table 4. Batteries and chargers required

Minimum number of batteries	13		Minimum number of chargers	4
Required number of chargers	≥ 8		Required number of batteries	≥ 17

In Fig.6 the swapping station´s load profile is shown for both daily simulations. The grey line shows the load profile when the swapping station operated with the minimum number of chargers (4) and with 17 batteries. The black line shows the load profile when the swapping station operated with the minimum number of batteries (13) and 8 chargers.

In Fig.6 it can be seen how, although for both combinations the energy supplied to swapping station was the same, the demand profile of the swapping station was affected by the number of chargers and batteries used.

For the simulation where the minimum number of batteries was considered (black line in Fig.6), two demand peaks of 349kW were obtained (8 chargers with 43.64 kW power rating were used). The peaks in demand coincided with the battery swap demand peaks showed in Fig.4.

For the simulation where the minimum number of chargers was considered (grey line in Fig.6), a flatter demand profile was obtained, which remained constant almost during all the simulated day at 174.56kW (when 4 chargers with 43.64 kW power rating were used).

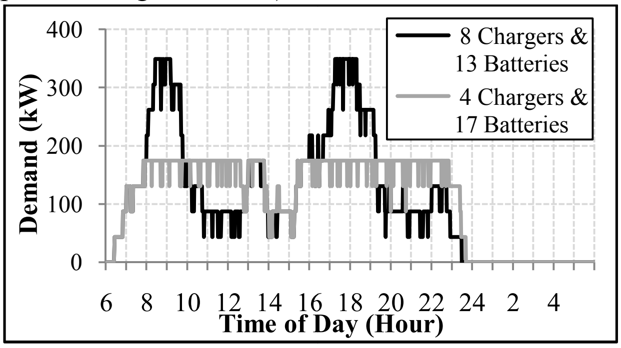

Fig.6 Load profile of a battery swapping station

5 Conclusion

A JAVA™ software tool was developed for the calculation of the minimum number of batteries and chargers required to satisfy a swapping station's battery daily demand. The tool runs daily simulations where the EVs arrival time and the depleted batteries' SoC are modelled as random numbers. The simulated chargers are monitored allowing the tool to plot the swapping station's electricity load profile.

A case study was conducted and the minimum number of required batteries and chargers calculated. The swapping station required a minimum number of 13 batteries (with a number of chargers ≥ 8) or a minimum number of 4 chargers (with a number of batteries ≥ 17).

The effect of the number of chargers and batteries on a swapping station's load profile was shown through a second case study. Two daily simulations were run, one using the minimum number of required batteries and the second simulation using the minimum number of required chargers (obtained from the first case study). For the same energy supplied to the swapping station, the number of chargers and batteries determined the shape and the peak demand values of the load profiles.

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Appendix:

The software tool computational procedure to obtain the minimum number of batteries and chargers required in a swapping station is shown in Fig. 7.

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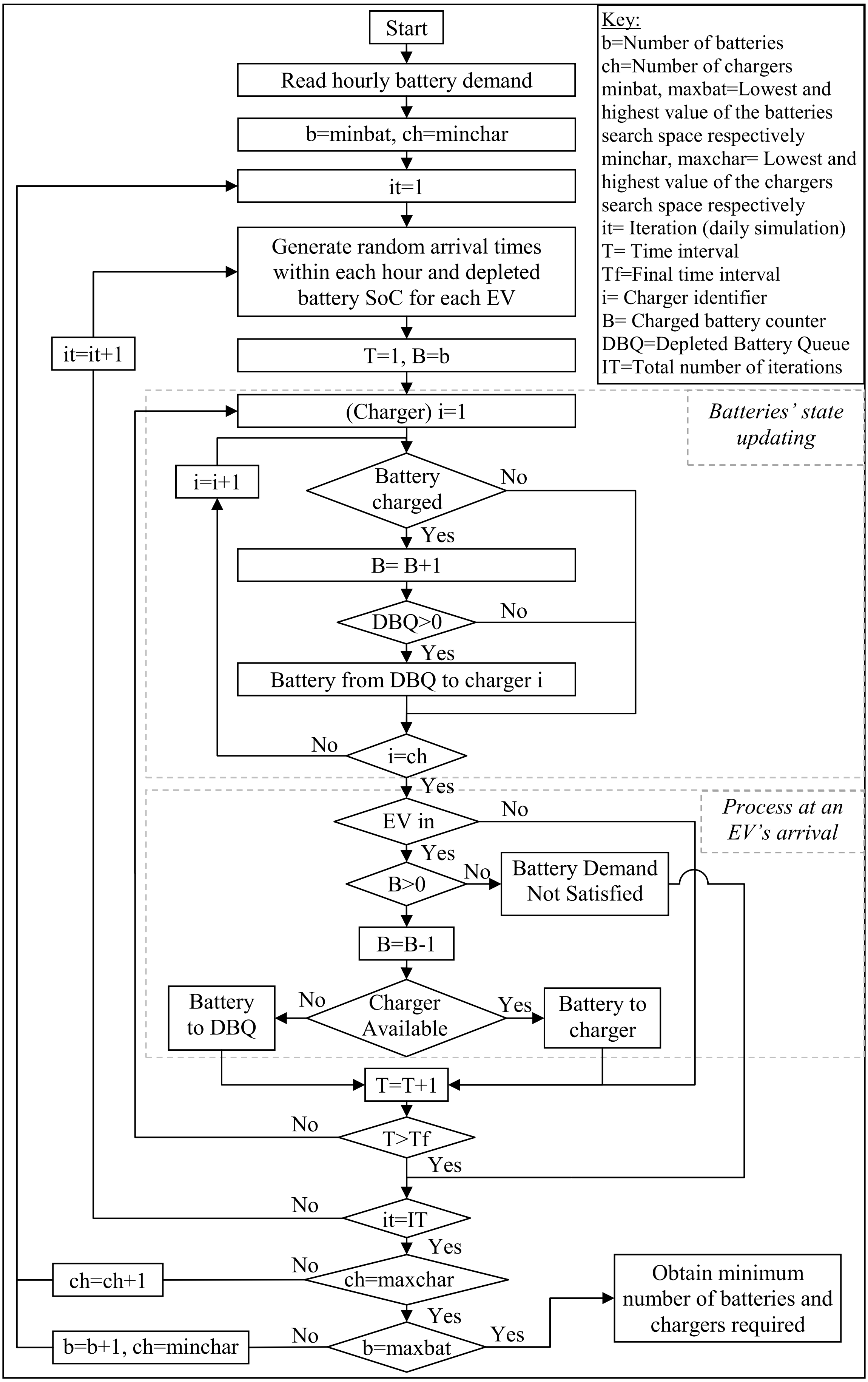

Fig. 7 Software tool computational procedure

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