Power & Energy Ratings Optimization in a Fast-Charging Station for PHEV Batteries

M. de Freige, M. Ross, G. Joos, M. Dubois

Abstract—**The design and simulation of a fast-charging station in steady-state for PHEV batteries has been proposed, which uses the electrical grid as well as two stationary energy storage devices as energy sources to recharge the PHEV battery. The two energy storage devices comprising the fast-charging station are a supercapacitor and a flywheel energy storage. The current paper justifies the selected power and energy ratings of the respective charging station resources in order to charge the PHEV battery with a maximum capacity of 15 kWh from 20% to 95% of its state-of-charge in a maximum duration of 15 minutes. After the charging stage, the storage devices are replenished in a maximum duration of 7.5 minutes. The methodology, results and its application are presented.**

Index Terms—**Energy, fast charging station, Energy Storage Systems, PHEV**

I. Introduction

With the increasing interest in green technologies in transportation, plug-in hybrid electric vehicles (PHEV) have proven to be the best short-term solution to minimize greenhouse gases emissions [1]. Fast-charging configurations have been proposed in order to charge PHEV batteries in durations ranging between 10 and 30 minutes [2], and some prototypes have already been tested [3, 4]. In particular, a configuration that uses the electrical grid and two energy storage devices has been proposed [5] that is composed of a flywheel and a supercapacitor [6, 7], as shown in Figure 1. The separate energy sources and battery technologies are all connected in parallel, although they are operated by the same controller. The current paper focuses on the selection of the energy ratings in the respective energy storage system technologies in order to charge a PHEV battery with maximum capacity of 15 kWh from 20% to 95% of its state-of-charge. An additional case scenario is also demonstrated at the end. The methodology and its application are presented in the subsequent sections.

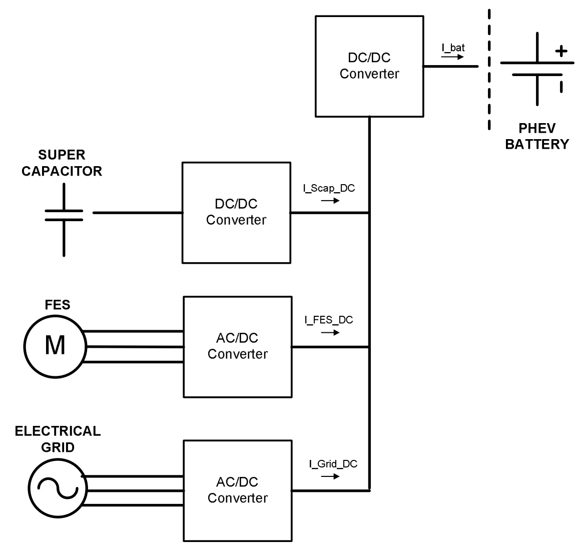

Fig. 1. Charging station Configuration.

II. Problem Definition

A. Charging Station Operation

In order to manage the charging station's energy sources, many topologies can be derived, but both are composed of a PHEV battery charging period followed by a period to recharge the station's Energy Storage Devices (ESD). This paper considers a charging algorithm shown in Figure 2. The blue lines for each axis show the power flow for each element of the charger, the grid, and the PHEV battery. Positive power represents that the element is providing or discharging energy, whereas negative power represents that the units are charging.

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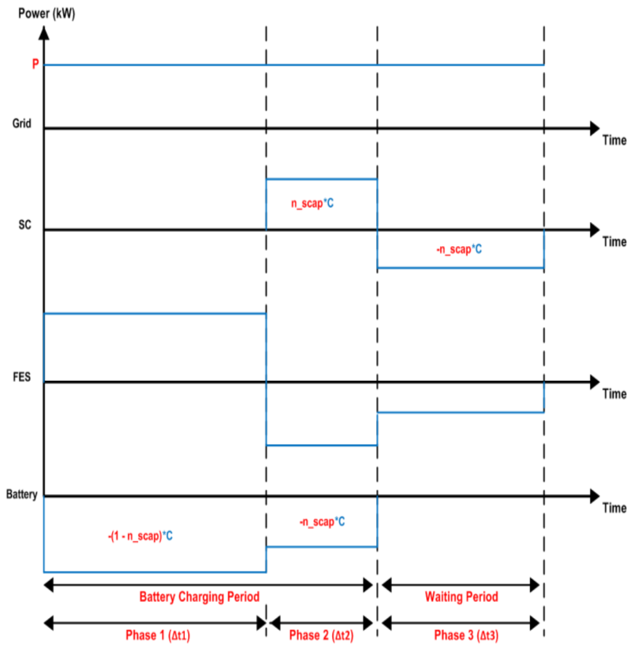

Fig. 2. Detailed Charging Station Operation, Divided into Three Phases.

The charging station phases are explained in detail below.

In Phase 1, the Flywheel Energy Storage (FES) and the electrical grid provide energy to the PHEV battery. The supercapacitor (SC) remains dormant in this phase.

In Phase 2, while the SC provides energy to the PHEV battery until its required capacity, the electrical grid recharges the FES.

In Phase 3, the electrical grid recharges the SC and the FES to their respective full capacities. It is also called the "waiting period" because during this time, no PHEV battery is allowed to be connected to the charging station. Once this phase is completed, the charging station is ready to charge another PHEV battery, which will continue in Phase 1.

B. Study Objective

The aim of this study is to determine the following parameters in the fast charging station (displayed in red in Figure 2):

- Battery charging time (min)
- ESD recharging time (min)
- FES contribution in energy (kWh)
- SC contribution in energy (kWh)

III. Methodology

As each parameter affects the parameters of other elements, the methodology of determining the appropriate ratings and times is outlined in different procedures, labeled *A*-*E*.

In Part *A*, the relation of the various parameters outlined in the "Study Objective" section must be determined. Since the parameters are all dependant on each other, they will be plotted versus the amount of grid power and the percentage of the total fast-charger that is composed of the SC. These two variables were selected because, from these, the other parameters can be easily identified or calculated.

The purpose of Part *B* is to extrapolate the point that will yield the minimum PHEV battery charging duration plus waiting time. From this, we can find the respective contributions of the FES and SC in the fast-charging station in Part *C*. Finally, in Parts *D* and *E*, we calculate the remaining grid and ESD parameters, respectively.

A. Needed Characteristics

The study begins by plotting the previous parameters as a function of the grid power P_{Grid}, and the proportion of energy provided by the supercapacitor, n_{Scap}. The figures of the various parameters versus P_{Grid} and n_{Scap} are provided in Figures 3-6.

B. Grid Power and Supercapacitor Contribution Choice

From the battery charging time and ESD recharging time characteristics (shown in Figures 3 and 4, respectively) the $P_{Grid,}$ and n_{Scap} that yield the minimum battery charging duration and minimum ESD recharging duration was determined.

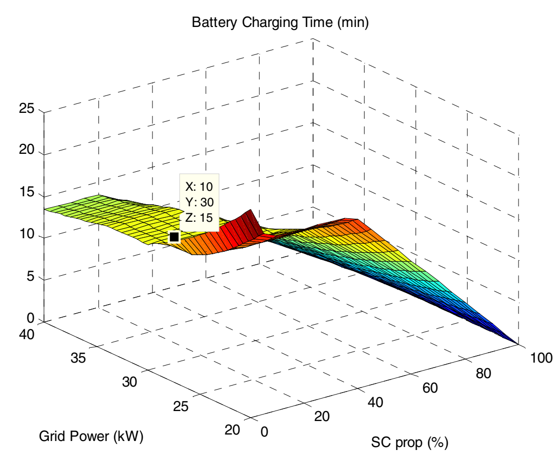

Fig. 3. Battery Charging Time Characteristic. A higher value indicates a higher battery charging time for that level of grid power and percentage of supercapacitor in the charging station.

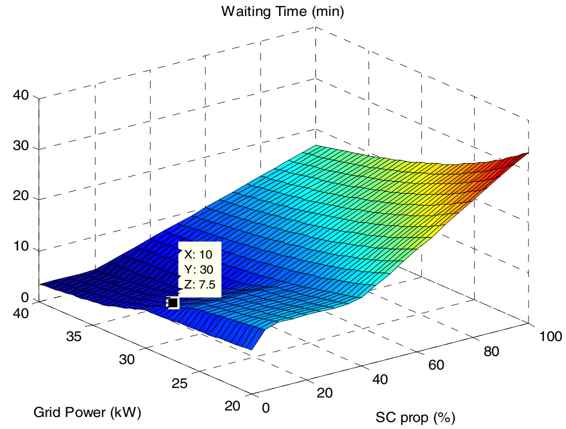

Fig. 4. Waiting Time Characteristic. . A higher value indicates a higher battery charging time for that level of grid power and percentage of supercapacitor in the charging station.

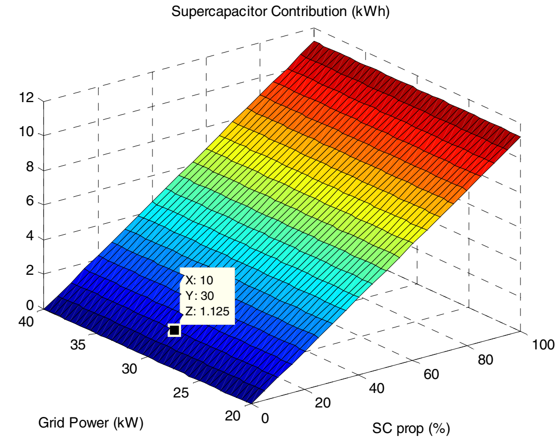

Fig. 6. SC Energy Contribution Charging Characteristic. The height indicates the amount of energy that originates from the SC that is used to charge the PHEV battery.

C. ESD Energy Contributions

From the FES and SC energy contribution characteristics (shown in Figures 5 and 6, respectively), we find the FES energy contribution, E_{FES}, and the SC energy contribution, E_{SC}, corresponding to P_{Grid} and n_{Scap} found previously.

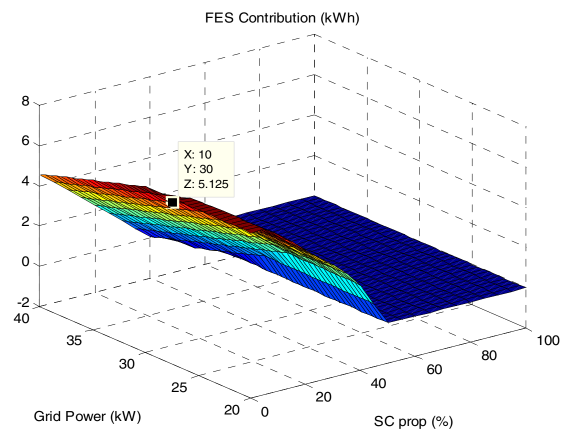

Fig. 5. FES Energy Contribution Characteristic. The height indicates the amount of energy that originates from the FES that is used to charge the PHEV battery.

D. Grid Parameters Calculations

The charging station is designed to charge PHEV batteries with a maximum capacity of $E_{Bat,max}$. The maximum duration of operation of the grid in Phase 1, Δt_{Grid}, is found as follows:

$$\Delta t_{Grid} = \frac{E_{Bat,max} - E_{FES} - E_{SC}}{P_{Grid}}$$

The charging station also operates with a voltage V_{DC} on the DC side. The grid current, I_{Grid}, is found as follows:

$$I_{Grid} = \frac{P_{Grid}}{V_{DC}}$$

E. ESD Parameters Calculations

The ESD maximum currents (I_{FES}, I_{SC}) and durations of operation (Δt_{FES}, Δt_{SC}) must satisfy constraints (1) to (4) mentioned below.

The time of operation of the ESD must be smaller than the minimum battery charging time, Δt_{Bat} (found in Part *A*):

$$\Delta t_{FES} + \Delta t_{Scap} \leq \Delta t_{Bat} \tag{1}$$

The sum of the grid and ESD currents must equal the maximum PHEV battery charging current, $I_{Bat,max}$ (that can be found on the battery datasheet):

$$I_{FES} + I_{Scap} = I_{Bat,max} - I_{Grid} \tag{2}$$

Finally, the ESD energies must satisfy the following relations:

$$V_{DC} \cdot I_{FES} \cdot \Delta t_{FES} = E_{FES} \tag{3}$$

$$V_{DC} \cdot I_{SC} \cdot \Delta t_{SC} = E_{SC} \tag{4}$$

IV. APPLICATION

A. Charging Station Sources Ratings

The described methodology is now applied to find the ESD and grid parameters of a fast charging station that charges PHEV batteries with maximum capacity of 15 kWh from a minimum of 20% to a maximum of 95% SOC (therefore $E_{Bat,max}$ = 11.25 kWh), maximum charging current of 125 A (therefore, $I_{Bat,max}$ = 125 A), and with a DC bus voltage of 600 V (therefore V_{DC} = 600 V) to satisfy the SAE J1772 standard [8].

Using the graphs obtained in Section III, the respective values for $P_{Grid,}$ and n_{Scap} that yield the minimum total time duration of the fast-charging cycle is determined to be:

$$P_{Grid} = 30 \text{ kW}$$

$$n_{Scap} = 10 \text{ \%}$$

Using these values, the remaining parameters are determined to be as follows:

- Battery charging duration: 15 minutes
- ESD recharging duration: 7.5 minutes

The results are summarized in Table I.

TABLE I
GRID AND ESD PARAMETERS

	Grid	*FES*	*SC*
Maximum Duration of Operation (min)	10	10	5
Maximum Power (kW)	30	30.75	13.5
Maximum Energy (kWh)	5	5.125	1.125

B. Second Design Example

With the designed charging station, a 12.5 kWh PHEV battery charged from 27% to 92% SOC would require the sources energy management and phase durations shown in Table II. Positive and negative quantities indicate whether the device delivers or absorbs energy.

TABLE II
CHARGER ENERGY MANAGEMENT FOR THE BATTERY

	Complete Charging Station Cycle			
	PHEV Battery Charging Period		*ESD Charging Period*	
	Phase 1	*Phase 2*	*Phase 3*	*Total*
Duration (min)	10	3.125	3.125	16.25
Grid Energy (kWh)	5	1.5625	1.5625	8.125
SC Energy (kWh)	0	0.8125	-0.8125	0
FES Energy (kWh)	2.3125	-1.5625	-0.75	0
Battery Energy (kWh)	**-7.3125**	**-0.8125**	**0**	**8.125**

V. CONCLUSIONS

The described methodology revealed to be successful to find the power and energy ratings of a fast-charging station for PHEV batteries that uses, in addition to the grid, one or more stationary energy storage devices. The power drawn from the grid is minimized, the battery charging process does not exceed 15 minutes, and the replenishment of the storage devices takes no longer than 7.5 minutes. These charging and full-cycle times of the charging station conform to the Level III fast-charger standard, as outlined in the SAE J1772 standard.

An advantage of a graphical representation of how the various parameters are affected by other parameters in the design of the fast-charging station can help one visualize the dependency of the various design parameters. From this, it is easy to visualize the effects of changing the grid power or composition of the charging station. Future work will involve changing the technologies of the charging station, and changing the capacities of the PHEV batteries to closer match battery electric vehicle (BEV) capacities.

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