Energy Management & Scheduling in a Fast Charging Station for PHEV Batteries

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

Abstract-- **The current paper focuses on the energy management in a fast charging station for PHEV batteries; that uses in addition to the grid a flywheel energy storage and a supercapacitor; with main objective to minimize the duration of the battery charging process and the time required to recharge the storage devices afterward. The designed station is capable to recharge PHEV batteries with capacities lower or equal to 15 kWh from a minimum of 20% to a maximum of 95% of the battery state-of-charge in a maximum duration of 15 minutes. After a battery has been charged, a waiting period (during which no cars are allowed at the charging station) of a maximum duration of 7.5 minutes is required. During this period, the storage devices are being recharged to their maximum. A scenario displaying the charging process of two different PHEV batteries is presented with the simulation results.**

Index Terms—**Energy management, fast charging, PHEV battery, flywheel emulation**

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]. Despite such interest conventional vehicles drivers are still reluctant in using this new technology mainly because of the long duration (4-8 hours) required to charge PHEV batteries with the currently existing Level I and II chargers [11]. For this reason Level III fast charging stations capable to reduce the charging duration to 10-30 minutes are being designed [7, 12]. The current paper focuses on the energy management of a configuration employing a supercapacitor (SC) [5, 10] and a flywheel (FES) [8, 9, 10] in addition to the electrical grid [2, 6] with the objective to achieve the minimum battery charging and energy storage recharging durations. The control of a FES in high power systems is not easy to implement, so an alternative would be to emulate a FES using a PMDC machine. Afterwards an algorithm that minimizes durations along with its mathematical formulation will be proposed, and then its application in fast charging technology will be illustrated by mean of an example. Simulations and results are also presented.

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II. FLYWHEEL EMULATION

The FES control could be the object for future work to be done for the charging station design improvement. As an alternative it could be emulated by a PMDC (Permanent Magnet DC Machine). Such operation would considerably decrease the system size and cost [3]. The FES system will thus be replaced by a DC machine as shown in figure 1 below.

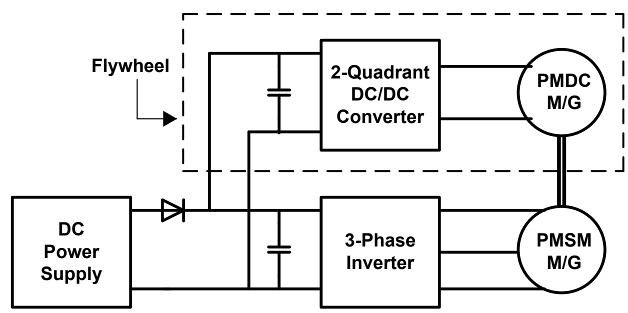

Fig. 1. Flywheel Emulation Using a PMDC [3]

The power flow in the above system is bidirectional. Every power transfer is done through the permanent magnet synchronous machine (PMSM) that can act as motor and generator. The DC power supply not only imposes the dc bus voltage, but also compensates for the system losses.

It is reminded that the kinetic energy dW (in J) stored in the above system with moment of inertia J_F (in $Kg.m^2$) and rotating from one speed ω_1 to another speed ω_2 (in rad/s) is expressed as [4]:

$$dW = 0.5\,J_F.(\omega_2^2 - \omega_1^2)$$

The above system is designed to operate in three modes based on the stored energy using the above formula: charge, discharge, and no charge [3]:

In the charge mode the power flows from the dc bus to the PMDC through the PMSM. In such case the DC machine is accelerated from the speed ω_1 to a higher speed ω_2.

In the discharge mode the power flows from the PMDC to the dc bus through the PMSM. In such case the DC machine is decelerated from the speed ω_2 to a lower speed ω_1.

In no charge mode the DC machine runs constantly at the lower speed ω_1, and there is thus no power flow.

III. Energy Management Algorithm

A charging station cycle is composed of two periods: during the first one a PHEV battery is being recharged in a duration that does not exceed 15 minutes, and then the charging station storage devices are being recharged by the grid in a duration that does not exceed 7.5 minutes.

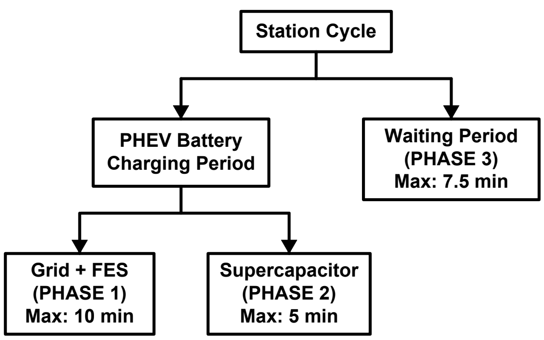

Fig. 2. Charging Station Cycle

A. Charging Station Cycle

As shown in figure 2 above, a charging station cycle is composed of three phases. The order of phases 1 and 2 has been set up by considering the fact that some PHEV users may have limited durations to spend at the charging station; for this reason most of the PHEV battery filling is done in the beginning of the cycle (phase 1).

In the first phase the FES and the electrical grid provide energy to the PHEV battery until 90% of its required capacity. The maximum duration of such phase is 10 minutes.

In the second phase, while the supercapacitor provides energy to the PHEV battery until its required capacity, the electrical grid is recharging the FES with a capacity determined by optimization. The maximum duration of such phase is 5 minutes.

During the third phase that lasts no more than 7.5 minutes the electrical grid is recharging the supercapacitor 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 the storage devices are fully recharged the charging station enters its standby mode until another PHEV arrives at the charging station to recharge its battery.

B. The Algorithm

In order to obtain the previous requirements the algorithm of figure 3 below is proposed. The abbreviations used in the flowchart are summarized in table I below.

TABLE I
ABBREVIATIONS USED IN FIGURE 3

Abbreviations	SC	FES	C_act	C
Expressions	Supercapacitor	Flywheel	Actual battery capacity	Total battery capacity

Instructions in blue mean that the storage device (flywheel or supercapacitor) is delivering power to the battery; whereas instructions in red mean that the storage device is being recharged by the electrical grid (same for figure 4 later).

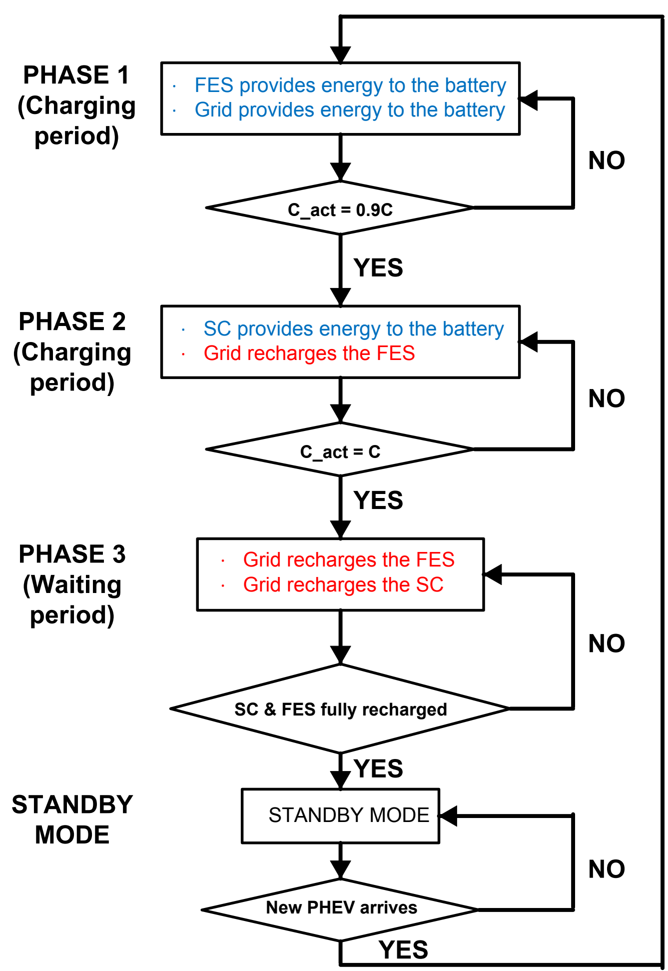

Fig. 3. Optimized Energy Management Algorithm

C. Standby Mode

The charging station enters this mode of operation once its two energy storage devices have been fully recharged. At this moment the FES rotates at constant speed Ω_o and thus there is no power transfer (dW = 0). The supercapacitor voltage continues to increase asymptotically to its rated voltage whereas its current tends asymptotically to 0. The charging station remains in such mode until the arrival of a PHEV at the station.

IV. Mathematical Formulation

The algorithm of figure 3 is represented graphically in figure 4 below. The parameters mentioned on it are explained in table II. The whole problem constraints (section IV.B) are based on such figure.

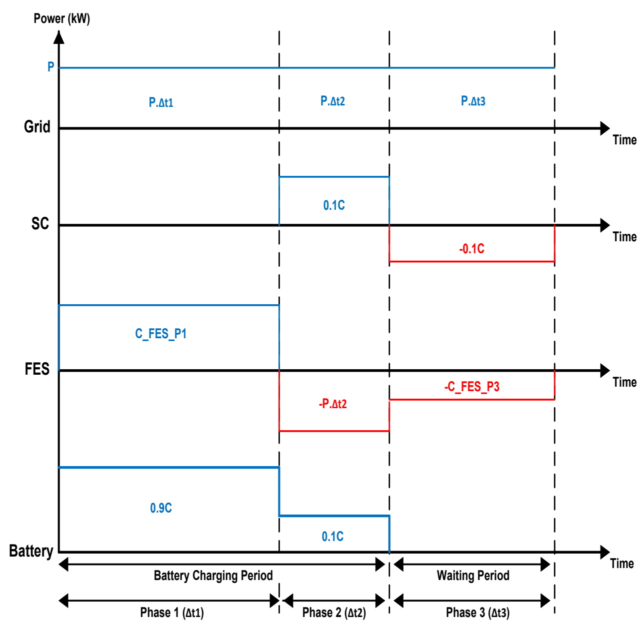

Fig. 4. Detailed Charging Station Cycle

A. Optimization Function

The charging station is designed to charge PHEV batteries whose capacities fall in the range 10-15 kWh. Furthermore the batteries are charged from a minimum state of charge (SOC) of 20% to a maximum SOC of 95%. This implies that the maximum capacity to be provided to a PHEV battery is 11.25 kWh. During phase 1 the grid provides 5 kWh of the total 11.25 kWh, so the storage devices are providing the remaining 6.25 kWh as follow: 1.125 kWh from the supercapacitor during phase 2, and 5.125 kWh from the FES during phase 1.

Once a PHEV arrives at the charging station, the figure 4 parameters that need to be computed are listed in table II:

TABLE II
OPTIMIZATION PARAMETERS

Parameter Name	Phase 1 Duration (min)	Phase 2 Duration (min)	Phase 3 Duration (min)	FES capacity in phase 2 (kWh)	FES capacity in phase 3 (kWh)
Symbolic Notation	Δt_1	Δt_2	Δt_3	$C_{FES\text{-}P1}$	$C_{FES\text{-}P3}$
Variable Maximum	10	5	7.5	5.125	5.125

The optimization function can be written as:

$$f(\underline{x}) = \sum_{i=1}^{3} x_i$$

with

$$\underline{x} = [\Delta t_1 \quad \Delta t_2 \quad \Delta t_3 \quad C_{FES-P1} \quad C_{FES-P3}]^T$$

B. Problem Constraints

The constraints imposed on the above problem are of equality and inequality types. They are based on figure 5.

The supercapacitor capacity being much smaller than the FES one, the duration of phase 2 is smaller than the one of phase 1:

$$\Delta t_2 < \Delta t_1$$

The waiting period duration must never exceed the charging period one because the waiting time must also be minimized to satisfy clients' needs.

$$\Delta t_3 < \Delta t_1 + \Delta t_2$$

As already mentioned, in phase 1 the FES and the grid (that delivers a power p, in kW) are recharging the PHEV battery to 90% of its required capacity C.

$$p.\Delta t_1 + C_{FES\text{-}P1} = 0.9.C$$

In phase 3 the grid is recharging the supercapacitor and the FES:

$$p.\Delta t_3 - C_{FES\text{-}P3} - 0.1C = 0$$

The FES is providing energy to the PHEV battery during phase 1, and is being recharged by the grid during phases 2 and 3:

$$C_{FES\text{-}P1} - p.\Delta t_2 - C_{FES\text{-}P3} = 0$$

C. Problem Summary

The optimization problem to be solved based on the constrained mentioned previously can be written as follow:

$$f(\underline{x}) = \sum_{i=1}^{3} x_i$$

With:

- Variables: $\underline{x} = [\Delta t_1 \quad \Delta t_2 \quad \Delta t_3 \quad C_{FES-P1} \quad C_{FES-P3}]^T$

- Equality Constraints: $A_{eq}.\underline{x} = \underline{b_{eq}}$

$$\Leftrightarrow \begin{bmatrix} p & 0 & 0 & 1 & 0 \\ 0 & 0 & p & 0 & -1 \\ 0 & -p & 0 & 1 & -1 \end{bmatrix} \begin{bmatrix} \Delta t_1 \\ \Delta t_2 \\ \Delta t_3 \\ C_{FES-P1} \\ C_{FES-P3} \end{bmatrix} = \begin{bmatrix} 0.9C \\ 0.1C \\ 0 \end{bmatrix}$$

- Inequality Constraints: $A.\underline{x} < \underline{b}$

$$\Leftrightarrow \begin{bmatrix} -1 & 1 & 0 & 0 & 0 \\ 0 & 1 & -1 & 0 & 0 \\ -1 & -1 & 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} \Delta t_1 \\ \Delta t_2 \\ \Delta t_3 \\ C_{FES-P1} \\ C_{FES-P3} \end{bmatrix} < \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}$$

- Lower and Upper Bounds: $\underline{lb} < \underline{x} < \underline{up}$

$$\Leftrightarrow \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} < \begin{bmatrix} \Delta t_1 \\ \Delta t_2 \\ \Delta t_3 \\ C_{FES-P1} \\ C_{FES-P3} \end{bmatrix} < \begin{bmatrix} 10 \\ 05 \\ 7.5 \\ 5.125 \\ 5.125 \end{bmatrix}$$

V. SIMULATIONS & RESULTS

The previous algorithm is now applied to the following scenario: Two PHEV batteries are consecutively being recharged by the same charging station. Their respective technical specifications are presented below:

Battery #1 Specs:
Capacity: 15 kWh
Charging: 25 to 90% SOC (So only 9.75 kWh are required)
Nominal voltage: 200V
Maximum charging voltage: 233.2 V
Minimum voltage: 166.5 V
Maximum charging current: 300 A

Battery #2 Specs:
Capacity: 13 kWh
Charging: 30 to 95% SOC (So only 8.45 kWh are required)
Nominal voltage: 180V
Maximum charging voltage: 210 V
Minimum voltage: 150 V
Maximum charging current: 280 A

A. Optimal Energy Management

The optimal energy managements that will minimize the charging durations of both battery vehicles as well as the storage devices recharging durations are shown in tables III and IV below.

TABLE III
OPTIMAL ENERGY MANAGEMENT FOR PHEV BATTERY 1

	COMPLETE CYCLE			
	CHARGING PERIOD		*WAITING PER*	
	PHASE 1	*PHASE 2*	*PHASE 3*	*TOTAL*
Duration (min)	10	4.75	4.75	19.5
Grid Energy (kWh)	5	2.375	2.375	9.75
Scap Energy (kWh)	0	0.975	-0.975	0
FES Energy (kWh)	3.775	-2.375	-1.4	0
Battery Energy (kWh)	8.775	0.975	0	9.75

TABLE IV
OPTIMAL ENERGY MANAGEMENT FOR PHEV BATTERY 2

	COMPLETE CYCLE			
	CHARGING PERIOD		*WAITING PER*	
	PHASE 1	*PHASE 2*	*PHASE 3*	*TOTAL*
Duration (min)	10	3.45	3.45	16.9
Grid Energy (kWh)	5	1.725	1.725	8.45
Scap Energy (kWh)	0	0.845	-0.845	0
FES Energy (kWh)	2.605	-1.725	-0.88	0
Battery Energy (kWh)	7.605	0.845	0	8.45

B. Charger Characteristics

Figure 6 below displays the charger characteristics evolution during the two cycles of the charging station.

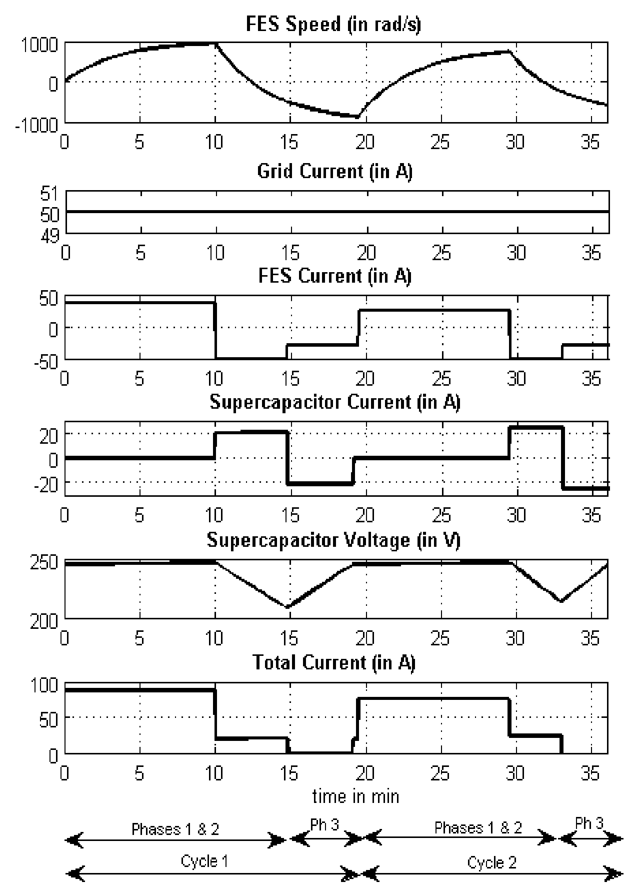

Fig. 5. Charging Station Operation during the Complete Scenario

The application of the proposed algorithm in fast charging is visible on figure 5 above for both PHEVs; it displays two cycles that are very similar to figure 4:

During phase 1 of a cycle the grid and the FES are providing energy to the battery until it is charged to 90% of its required capacity.

During phase 2 of a cycle the supercapacitor is providing energy to the battery until it is fully charged while the grid is partially recharging the FES.

During phase 3 of a cycle the supercapacitor and the flywheel are being recharged by the grid.

C. Batteries Characteristics

The PHEV batteries voltage, current, and state-of-charge (SOC) evolutions during the two cycles are displayed in figure 6 below.

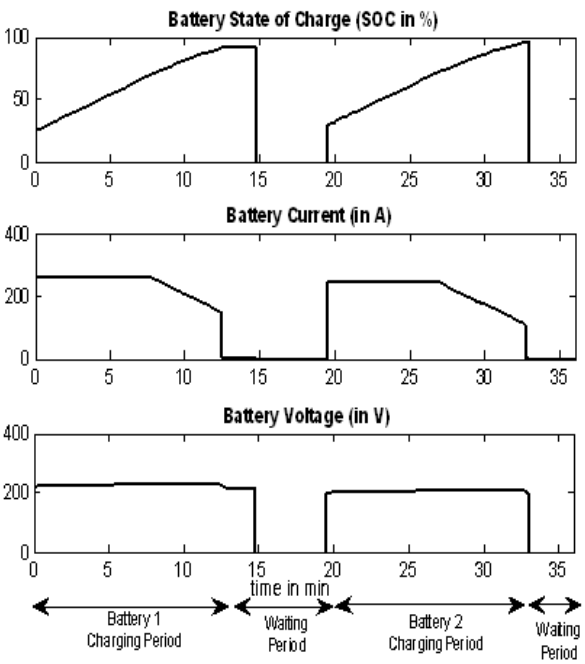

Fig. 6. Batteries 1 and 2 Characteristics Evolutions

It can be seen that both charging durations are below 15 minutes: while the first PHEV battery has been charged from 25% to 90% of its capacity in 14.75 minutes, the second PHEV battery has been charged from 30% to 95% of its capacity in 13.45 minutes. Furthermore the second PHEV had to wait only 4.75 minutes to allow the charging station storage devices to get fully recharged.

VI. CONCLUSION

The fast charging station energy management that minimizes the battery charging duration as well as the waiting duration between two consecutive charging has been shown. The maximum charging time obtained to charge a PHEV battery from 30% to 95% of its SOC is 14.5 minutes and the maximum waiting period duration obtained is 4.5 minutes. Such results have been obtained with a configuration that uses the electrical grid, a supercapacitor, and a flywheel energy storage.

APPENDIX

A. Grid Parameters

- *AC Side*: V_{rms} = 240 V
- *DC Side*: dc bus voltage = 600 V

B. Supercapacitor Parameters

- C_{scap} = 150 F
- $V_{scap,ref}$ = 245 V

REFERENCES

[1] "Hybrid Cars & Alt Fuels," *About.com*, para. 1, 2010. [Online]. Available:http://alternativefuels.about.com/od/glossary/g/pluginhybrid.htm

[2] M. de Freige, G. Joos, M. Dubois, "Design and Simulation of a Fast Charging Station for PHEV/EV Batteries," in *Electrical power and Energy Conference, 2010. IEEE, Aug 25-27, 2010*

[3] B. Vafakhah, M. Masiala, J. Salmon, A. Knight, "Emulation of Flywheel Energy Storage Systems With a PMDC Machine," in *International Conference on Electrical Machines*, *2008, Vilamoura*

[4] John D. Boyes, Nancy H. Clark, "Technologies for Energy Storage Flywheels and Super Conducting Magnetic Energy Storage," in *Power Engineering Society Summer Meeting, 2000. IEEE, Jul 16-20, 2000*

[5] A. Rufer, "A Supercapacitor-Based Energy-Storage System for Elevators With Soft Commutated Interface," in *Industry Applications Conference*, *Sept- Oct 2002*

[6] M. R. Dubois, M. Desjardins, L. Tremblay, '' FRESS : Fast rate energy storage system'', US Patent Application 61/233,664, submitted 13 August 2009.

[7] *Electric Vehicle Conductive Charge Coupler,* SAE J1772, Recommended Practice, Draft Document in progress 2009

[8] Investire-Network, "Investigation on Storage Technologies for Intermittent Renewable Energies: Evaluation and Recommended R&D Strategy," Jun. 17, 2003. [Online]. Available: http://www.itpower.co.uk/investire/pdfs/flywheelrep.pdf

[9] John D. Boyes, Nancy H. Clark, "Technologies for Energy Storage Flywheels and Super Conducting Magnetic Energy Storage," in *Power Engineering Society Summer Meeting, 2000. IEEE, Jul 16-20, 2000*

[10] Bo. Yang, Y. Makarov, J. Desteese, V. Viswanathan, P. Nyeng, B. McManus, and J. Pease, "On the Use of Energy Storage Technologies for Regulation Services in Electric Power Systems with Significant Penetration of Wind Energy," in *Electricity Market, 2008. EEM 2008. 5th International Conference on European May 28-30, 2008, Lisboa*

[11] L. Dickerman, J. Harrison. "A New Car, a New Grid,"*IEEE power & energy magazine*, vol. 8, no. 2, pp. 58-59, March/April 2010

[12] ZIP Charging Stations for PHEV's or LSV's, "Powering Transportation with Renewable Energy Sources" *Eco-Trans Alliance*. [Online]. Available: http://www.ecotransalliance.com/ev-phev-chargers.html.