Design and Simulation of a Fast Charging Station for PHEV/EV Batteries

G. Joos and M. de Freige, Jr.
Department of Electrical Engineering
McGill University
Montreal, Quebec H3A 1A5, Canada
geza.joos@mcgill.ca & makram.defreige@mail.mcgill.ca

M. Dubois
Department of Electrical Engineering
Laval University
Sainte-Foy, Quebec G1V 0A9, Canada
mrdubois@gel.ulaval.ca

***Abstract* - The importance given to the market integration of PHEV (Plug-in-Hybrid Electric Vehicle) and EV resulted in an increase in the interest for the fast charging technology of such car batteries. The paper reviews work recently conducted in this area and proposes a fast charging station using a flywheel energy storage and a supercapacitor as energy storage devices. Design issues and simulation results for a typical Level III charger are presented.**

Index Terms – Road vehicle electric propulsion; Flywheel; Power capacitor

I. INTRODUCTION

A PHEV is a hybrid automobile with a higher-capacity battery that can be recharged by connecting vehicle to the electrical network [1]. Because of their short-term economic and environmental advantages, nearly all major carmakers have invested significantly in PHEV development. The charging of such vehicle batteries requires the design and implementation of charging stations. The current paper reviews proposed standards and implementation requirements that have been conducted in the PHEV/EV charging technology, and then proposes a fast charging station design using a flywheel (FES) and a supercapacitor (SC) as energy storage devices. The simulation and results for the charging process of a vehicle battery are given.

II. BACKGROUND

A. PHEV Charging Equipment

1) Equipment Role: A very important impacts concerns the development of the charging equipment for the market integration and daily use of PHEVs. It is essential that this equipment has the ability to:

a) Quickly charge the vehicle battery
b) Modulate the electricity prices with the time of day
c) Detect the state of charge (SOC) of the vehicle battery
d) Automatically bill for the electricity delivered
e) Adapt to various battery types and car models

2) Equipment Parts: The most critical problem in charging PHEV/EV batteries is the car owner and public safety. Indeed the cords connecting house plugs or road stations to vehicle could cause electrical hazards. For this reason vehicle supply equipments have been conceived in order to avoid such problem, and they consist of the three following devices [2]:

a) Supply Device: Principle component of the charging station, it draws power and provides shock protection.
b) Power Cord: It is a cable that contains electrical current and communication signals from the charging device to the connector.
c) Connector: It is simply a plug on the power cord that links the supply equipment to the PHEV/EV charging socket.

3) Charging Station Classification: For many years the Society of Automotive Engineering (SAE) has been working on standard J1772, which classifies charging stations into 3 categories [2]:

a) Level I: charger is on-board and provides AC voltage 120V or 240 V with maximum current of 15 A (standard home outlet), maximum power of 3.3 kW.
b) Level II: charger is on-board and provides AC voltage 240 V with maximum current of 60 A, maximum power of 14.4 kW.
c) Level III: charger is off-board. The charging station provides DC voltage directly to the battery via a DC connector, with a maximum power of 240 kW. Level III chargers are fast chargers. The maximum power supplied for Level III charging equipment should be capable to replenish more than half of the capacity of an EV battery in less than half an hour.

B. History of Fast Charging

The importance of a network of charging stations is already established as a critical part of the PHEV and EV technologies. In the future, charging stations may play the same role as gas stations today. In Israel (2011), Denmark (2011), Australia (2012) and Portugal, governments have already set targets in place for a large penetration of charging stations in the urban environment [3], [4]. US Company Better Place is a leader in this field and plans to install hundreds of thousands of Level I and Level II AC charging stations in these countries.

General Motors plans to release the Chevy Volt EV in 2011, with a battery capacity of 16 kWh and a level I, on-board charger of power 3.3 kW [5].

A lack of fast charging units exists. As an alternative, urban facilities have been proposed where the discharged car batteries would be swapped with charged battery packs. However, at the recently held Alternative Fuels and Vehicles conference, a panel of representatives from some American electric car makers suggested that they would prefer fast

2010 IEEE Electrical Power & Energy Conference
978-1-4244-8188-0/10/$26.00 ©2010 IEEE

charging stations to the battery swapping scenario. The impact on battery degradation is a critical parameter that needs to be taken into account [6].

III. Fast Charging Considerations

A. The Level III Charger

Among the three classes of charging stations, the level III is the most interesting and practical one for installations in public places like commercial areas since it enables an easier integration of PHEVs and EVs into the market. In the future such stations may play the same role as gas stations today. For this reason, many developed countries are actually planning on using Level III, off-board, quick chargers, especially in Western Europe [7]. In Japan, the Tokyo Electrical Power Company has announced the installation of 200 10-minutes high power chargers for 2010, which will coincide with the introduction of the Mitsubishi i-Miev EV, which is already advertized with a quick-charge DC plug [8]. This is the result of a structural characteristic of Tokyo, where drivers do not have access to a plug at their homes to charge their cars.

B. Existing Prototypes

Some American companies have already built prototypes of such fast charging stations: a prototype that boasts 10 min charge time is expected to be launched during the third quarter of 2010 [9], and the LSV-100 Zip prototype that can charge in less than 30 min [10]. In Europe in January 2010 Renault-Nissan announced its success in the development of a fast charging station that is capable to replenish 80% of an EV car battery in less than 30 min [11].

C. Advantages and Drawbacks

1) Benefits: Besides charging a battery car to 80% of its SOC in typically 15 minutes [12], fast charging also decreases operating costs and increases productivity in two ways [13]:

a) Fast chargers are known to be more efficient than conventional chargers, and charging with less overcharging increases the battery efficiency.

b) With fast charging, the average battery SOC (State of Charge) is kept higher, which increases the vehicle speed.

2) Issues: The main issues in fast charging reside in the four main failure mechanisms of industrial lead acid batteries [13]:

a) Positive Active Material (PAM) Shedding
b) Corrosion of the positive plate grid
c) Imbalance among battery cells
d) Suffocation of negative plate

D. Conventional Charging Schemes

In a bidirectional battery charger, charging can be accomplished in several ways [14].

1) Constant Current/Constant Voltage Mode: It is done in two phases. The battery is first charged at constant current mode to typically 70% SOC then it is charged in constant voltage mode where the current is less than the set current.

2) Fast Charging Mode: Several algorithms and methods have been found in order to implement fast charging, and among them is a fully digitized smart method involving a combination of high continuous constant charging current and some charging pulse current. Such technique considers the actual charge state of the battery and the battery previous charges and discharges [15]. However the method that has revealed as being the most practical one and as having the best efficiency and the shortest charging time is the pulse-charged method. It basically consists of creating a large-time charging pulse that is immediately followed by a very short-time discharging pulse, followed by a “waiting period” [14].

IV. Storage Devices

Level I and II chargers are known to be slow because they draw their power from only a single AC source: the electrical grid [16]. A way to make a charger faster as will be the case in the Level III category is to let the charger draw power from multiple AC and/or DC sources. These last sources are referred to as energy storage devices due to their capability to accumulate some energy for a finite duration before restoring it to the circuit.

A. Stationary Storage Devices

The typical devices used as energy storage are displayed in Table I below [17].

TABLE I

COMPARISON OF SOME ENERGY STORAGE TECHNOLOGIES

Storage Technology	Life time (Cycles)	Efficiency (%)
Lead-Acid batteries	200-300	75
Sodium-Sulfur (NaS) batteries	2000-3000	89
Metal-Air batteries	100-200	50
Li-Ion batteries	300-500	95
Flow battery	1500-2500	75-85
Supercapacitors	$10^4 – 10^5$	93-98
FES	10^5 - 10^7	90

B. Pros and Cons

Such devices do not share the same pros and cons. Table II below displays the advantages and drawbacks of the energy storage devices of Table I [18]:

V. Design Considerations

The choice among all the previous storage technologies is based on the following energy and performance requirements.

A. Energy Requirements

The fast charging station to be designed can supply a maximum power of 240 kW.

TABLE II

FEATURES OF ENERGY STORAGE TECHNOLOGIES

Storage	Advantages	Disadvantages

Technology		
Lead-Acid batteries	High capacity, low volume energy density, low capital cost, long life time	Low efficiency, potential adverse environmental impacts
Sodium-Sulfur NaS batteries	Very high energy and power capacity, high energy density, long life time	Production cost, safety concerns
Metal-Air batteries	Very high energy density	Few rechargeable batteries available
Li-Ion batteries	Very high efficiency and energy density	Low number of life cycles
Flow battery	Very high energy and power capacity, long life time	Low energy density, low efficiency
Supercapacitors	High efficiency	Low energy density, few power systems applications
Flywheel energy storage (FES)	High power capacity, short access time, long lifetime, low maintenance effort, high efficiency, small environmental impacts	Low energy density

Assuming that the grid has a voltage of $V_{rms,ll}$ = 208 V and current of I_{rms} = 15 A, and considering a unity power factor pf, then its maximum output power will be:

$$P = \sqrt{3}.V_{rms,ll}.I_{rms}.pf \Leftrightarrow P_{Grid} = 5.4 \text{ kW}$$

Hence the storage devices are required to provide a maximum output power of 234.5 kW. The fast charging station is designed to charge batteries of PHEV/EVs in a maximum duration of Δt = 20 min. So the maximum quantity of energy to be supplied by the local storage is:

$$E = P.\Delta t \Leftrightarrow E = 78.17 \text{ kWh}$$

B. Performance Requirements

The energy storage devices must also satisfy the following performance criteria in order to maximize the fast charging station efficiency:

1) Dynamic Device: Since the charging station operates for only 20 minutes (short duration), the storage devices must be able to charge and discharge in that period.

2) High Power Density: As a consequence of the previous requirement, the devices must also have a high power density in order to deliver a large amount of power for a short period of time.

3) High Efficiency: The charging station must meet its maximum possible efficiency. This last criterion depends on the main station parts: converters, storage devices. Therefore it is a must to consider high efficiency energy storage and conversion.

4) Environmentally Friendly: The device must have no or negligible bad impacts on the environment.

C. Chosen Devices

According to the previous comparison of energy storage devices, a possible option is to combine the supercapacitors and FES as the fast charging station energy storage devices. These lasts must be rated considering the energy requirement imposed above.

The formula that relates the supercapacitor voltage U (in V) and capacitance C (in F) to the energy E (in J) that can be stored in the supercapacitor is:

$$E = 0.5\, CV^2 \quad [1]$$

Hence the device must have a sufficiently high capacitance to discharge and charge in the time of the station operation (15-20 min), and it should be rated at high voltage.

The formula that relates the flywheel angular speed ω (in rad/s) and moment of inertia J (in $Kg.m^2$) to the energy E (in J) that can be stored in the flywheel is:

$$E = 0.5\, J\omega^2 \quad [2]$$

Hence the device must have a sufficiently high moment of inertia, and thus a big radius and it must rotate at high angular speed.

D. Operating Characteristics

The charging station is designed with the following parameters:

Charging power = 240 kW
DC bus voltage = 320 V
DC charging current = 800 A

VI. Proposed Design

A. Complete Design

The proposed charging station uses the grid current and two additional energy storage devices: a FES and a supercapacitor. The concept of a level III charging station with flywheel was proposed in [21]. The design is shown in figure 1 below:

B. Main Components and their Individual Control

1) Grid: Unlike Level I and II chargers, the Level III provides DC voltage and current [2]. For this reason the grid is interfaced with the charger bus via a rectifier that outputs a maximum current of 10A and maintains the DC bus voltage constant via a voltage regulator.

2) FES: Since a FES belongs to the rotating machines category, it can be modeled by any other rotating generator. The amplified speed error constitutes the reference current to be output by the FES. The interface with the dc bus is done via an AC/DC converter.

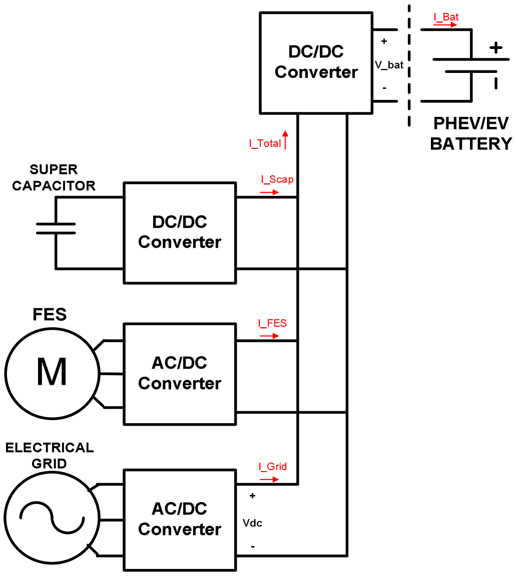

Fig. 1 Complete Charging Station

3) Supercapacitor: It is modeled as a capacitor with a resistor in parallel. The amplified voltage error constitutes the reference current to be output by the supercapacitor. The interface with the DC bus is done via a DC/DC converter.

4) Charger Output: The interface of the dc bus with the car battery is done via an output DC/DC converter. Indeed the converter input; or charger dc bus; is always kept constant whereas the output varies depending on the car battery maximum charge voltage. So the charger must adapt to the battery to be charged.

The control is done as follow: the amplified voltage error constituting the charging current must not exceed the maximum battery charging current. Also the charging voltage is bounded above by the largest battery charging voltage. These last two parameters are provided by the battery datasheet.

C. *Charging Station Control*

The grid side converter controls the dc bus voltage, and the current supplied is normally set to the value that the grid can supply. Consequently the two energy storage devices must provide the difference between the battery and grid currents. One option for the control of Fig. 1 in steady-state is the following: 90% of the energy comes from the FES and the remaining 10% are provided by the supercapacitor. Note that such proportions can be varied.

VII. Simulation Results

The charger has been simulated for a Li-ion battery car. The simulation has been run using Matlab/Simulink, and the parameters can be found in the appendix. The total time required to charge the battery from 20% to 95% SOC is 13.25 minutes.

A. *Battery Characteristics*

Fig. 2 below displays the evolution of the battery SOC (in %), the battery current (in A), and the battery voltage (in V), during the charging process.

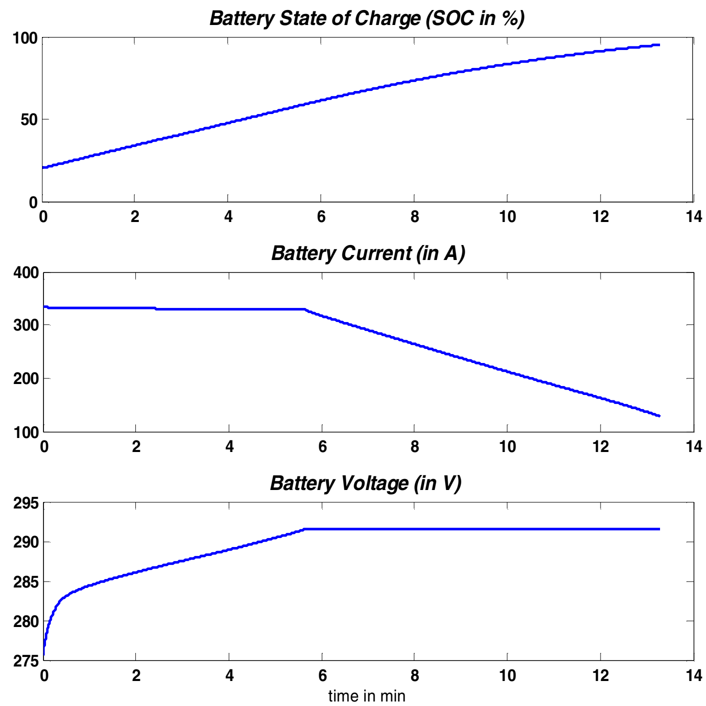

Fig. 2 Battery Characteristics Evolution

It can be seen that two charging phases occur: the first one is constant current and the second one is constant voltage which starts at approximately t = 5.5 min. Also the maximum battery charging current and voltages are not exceeded.

B. *Charger Characteristics*

Fig. 3 below displays the evolution of: the output DC/DC duty cycle (in %), and the grid, FES, supercapacitor, total currents (in A), and the DC bus voltage (in V) during the charging process.

It can be seen that the moment at which the constant voltage charging phase begins coincides with the moment the output DC/DC duty system cycle stabilizes.

VIII. Conclusion

The paper discussed works that have already been conducted in the PHEV/EV fast charging process. The simulation showed that the proposed design employing a FES and a supercapacitor falls well in the level III station category. Indeed a typical PHEV battery has been charged from 20% to 95% SOC in 13.25 minutes while remaining within equipment technical specifications and the output power does not exceed 240 kW.

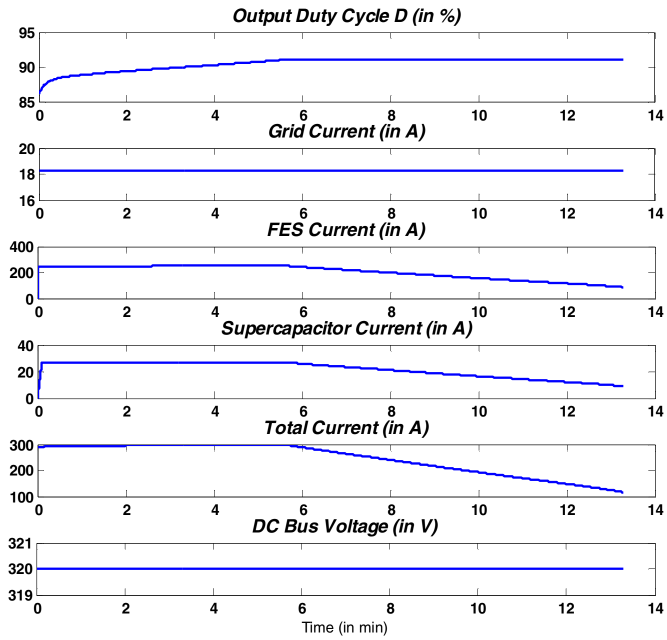

Fig. 3 Charger Characteristics Evolution

ACKNOWLEDGMENT

The authors wish to acknowledge the financial support provided by the National Science and Engineering Research Council (NSERC) Network of Centres of Excellence (NCE) Auto 21 grant, as part of a project entitled *Infrastructure for wide market adoption of PHEVs*, lead by Maxime Dubois, of Laval University, Canada.

REFERENCES

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

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

[3] David Ehrlich, "The electric car charging startup takes on its biggest project to date." *Better Place to charge up Australia* 2008. [Online]. Available:http://cleantech.com/news/3761/better-place-charge-australia

[4] Better place, "better place partners to bring electric vehicles to Australia," *better place partners to bring electric vehicles to Australia*. 2009 [Online]. Available: http://australia.betterplace.com/

[5] The Associated Press, "GM unveils Volt electric car." *cbc.ca* 2008. [Online]. Available:http://www.cbc.ca/technology/story/2008/09/17/gm-volt.html.

[6] J. Zhoua, P.H.L. Notten, "Studies on the degradation of Li-ion batteries by the use of microreference electrodes," *Journal of power Sources*, no. 177, p. 553-560, November 2007. [Abstract]. Available: http://www.sciencedirect.com/science?_ob=ArticleURL&_udi=B6TH1-4R5VYTM7&_user=458507&_rdoc=1&_fmt=&_orig=search&_sort=d&_docanchor=&view=c&_searchStrId=1167847484&_rerunOrigin=google&_acct=C000022002&_version=1&_urlVersion=0&_userid=458507&md5=460e364fdd7c0feece26ace30d7f89b3

[7] PHEVs Going International: Europe's Avere Conference, **"**PHEVs Going International: Europe's Avere Conference**"** *CalCars The California Cars Initiative – 100+ MPG Hybrids*. [Online]. Available: http://www.calcars.org/calcars-news/769.html

[8] Sam Abuelsamid (RSS feed), "More details on Michigan becoming initial market for Volt along with California." *autobloggreen*. 2010. [Online]. Available: http://green.autoblog.com/

[9] Electric Vehicle Fast Chargers - Level 3, "Electric Vehicle Fast Chargers - Level 3" *BTCPower*. [Online]. Available: http://www.btcpower.com/products-and-applications/electric-vehicle-chargers-level-3/.

[10] 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.

[11] 2010 Nissan Leaf electric car: In person, in depth - and U.S. bound**,** **"**2010 Nissan Leaf electric car: In person, in depth - and U.S. bound**"***Autoblog*. [Online]. Available:http://www.autoblog.com/2009/08/01/2010-nissan-leaf-electric-car-in-person-in-depth-and-u-s-b/.

[12] Henry Oman, "Making Battery Last Longer," *AES System Magazine, IEEE* , vol. 14, pp. 19-21, Sep. 1999.

[13] B. Dickinson and J. Gill, "Issues and Benefits with Fast Charging Industrial Batteries," in *Operational Benefits of Fast Charging Battery Conference on Applications and Advance,* Jan 11-14, 2000

[14] P. Husuan and C-L. Chen, Eds "A High-Efficiency Fast Charger For Lead-Acid Batteries" in *IECON 02 [Industrial Electronics Society, IEEE 2002 28th Annual Conference]***,** Nov 5-8, 2002

[15] J. Alvarez, J. Marcos, A. Lago, A. Nogueiras, J. Doval and C. M. Peiialver "A Fully Digital Smart and Fast Lead-Acid Battery Charge System" in *Smart Lead-Acid Battery Charge System: Power Electronics Specialist Conference, 2003. PESC '03. 2003 IEEE 34th Annual,* Jun 15-19, 2003

[16] "Plug-in Hybrid Electric Vehicle Charging Infrastructure Review," Nov 2008. [Online]. Available:http://avt.inl.gov/pdf/phev/phevInfrastructureReport08.pdf

[17] S. Lemofouet, A. Rufer, "A Hybrid Energy Storage System Based on Compressed Air and Supercapacitors with Maximum Efficiency Point Tracking (MEPT)" in *Industrial Electronics, IEEE Transactions, vol. 53, pp. 1105-1115,* Jun, 2006

[18] B. 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,* May 28-30, 2008

[19] R. Nave, "Energy in an Inductor," in *HyperPhysics*. [Online]. Available: http://hyperphysics.phy-astr.gsu.edu/HBASE/hph.html

[20] "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

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

APPENDIX

A. *Grid Parameters*

- *AC Side*: $V_{ll,rms}$ = 208 V
- *DC Side*: dc bus voltage = 320 V

B. *Supercapacitor Parameters*

- C_{scap} = 100 F
- $V_{scap,ref}$ = 400 V

C. *Battery Parameters*

- Maximum charging voltage = 291.5 V
- Maximum continuous charging current = 400 A
- Nominal voltage = 250 V
- Minimum voltage = 208 V