

Offline and Online Optimization of Plug-in Hybrid Electric Vehicle Energy Usage (Home-to-Vehicle and Vehicle-to-Home)

Florence Berthold^{*†}, Benjamin Blunier^{*}, David Bouquain^{*}, Sheldon Williamson[†], Abdellatif Miraoui^{*}

^{*}Transport and Systems Laboratory (SeT)

University of Technology of Belfort-Montbéliard

90010 Belfort Cedex, France

Emails: (florence.berthold, benjamin.blunier, david.bouquain, abdellatif.miraoui)@utbm.fr

[†] Power Electronics and Energy Research (PEER) group

Department of Electrical and Computer Engineering

1455 de Maisonneuve Blvd.W

Montréal, Québec H3G 1M8, Canada

Email: sheldon@ece.concordia.ca

Abstract—Plug-in Hybrid Electric Vehicles (PHEVs) are seen to be a step forward in vehicle electrification, to replace ICE-based conventional vehicles. On the one hand, using a PHEV means that a part of the vehicle energy comes from the grid or other sources, such as renewable energy, to charge the battery. On the other hand, increasing the number of nuclear and coal power plants to supply these new needs would shift the problem, and will not permit solving the problem of pollution or fossil fuel depletion.

This paper describes an offline optimization towards an online optimization control strategy for a PHEV connected/disconnected to home.

Index Terms—Control strategy, electric vehicles, dynamic programming, power generation scheduling, vehicle power systems.

I. INTRODUCTION

In the next few years the oil import from oil-rich countries is expected to fall. However, the emission part of transportation and electric power industries will increase further. This increase shows that using plug-in hybrid electric vehicles (PHEVs) is essential [1].

U.S. government and companies are conscious of changing conventional vehicles to PHEVs. For example, New York city is changing conventional taxicabs with Toyota Prius', to reduce 50% of green house gases. Furthermore, Google converted their corporate fleet of hybrid cars into PHEVs [2].

Using PHEVs are the outcome of energy production. According to J. Schlee [3], by 2050, about 60 % of personal car sales will be PHEVs. This will represent an increasment of 18 % of total electric load on the electricity grid.

This paper describes the optimization problem, which allows minimization of energy cost and explains the offline as well as online optimization. Section III provides 2 examples, which use these algorithms. Finally, the last section shows the comparison between the offline and online optimization.

II. OPTIMIZATION PROBLEM

The global model described in Figure 1 shows user's home with their PHEV. Home is connected to the grid and to N number of renewable energy sources. When the PHEV is connected to home, the battery can be charged either from the renewable energy source, or the grid, or both. This energy flow is called home-to-vehicle (H2V). The battery can also supply home loads, which in turn helps back-up the grid. This energy flow is called vehicle-to-home (V2H). When the PHEV is disconnected from home, the vehicle is propelled either by the battery, or the engine, or both.

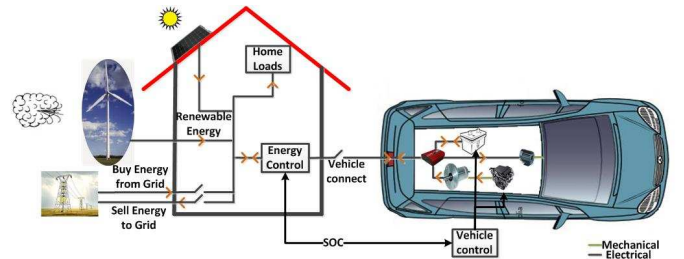


Figure 1. Global diagram

The optimization objective is to minimize the global energy cost, knowing that each energy flow has a specific price, which can vary during the day. The objective equation is given in (1), when N is the number of renewable energy sources connected to home.

The vehicle power is limited by the sizing of the different components, especially the state of charge (SoC) of the battery (2) and the power of the engine (3), where P_{fuel_max} is the maximum ICE power. Moreover, the on-board battery charger is limited by the home outlet power (4), where P_{grid_max} is the maximum grid power.

$$Cost_{energy} = \min \sum_{N=1}^{+\infty} P_{N_renewable} \cdot Cost_{N_renewable} + P_{grid} \cdot Cost_{grid} + P_{fuel} \cdot Cost_{fuel} \quad (1)$$

$$SoC_{min} \leq SoC \leq SoC_{max} \quad (2)$$

$$0 \leq P_{fuel} \leq P_{fuel_max} \quad (3)$$

$$0 \leq P_{batt} \leq P_{grid_max} \quad (4)$$

Table I
PHEV CHARGING LEVELS [4]

Level	Voltage (V)	Amperage (A)	Load (kW)
1	120	15	1.4
2	120	20	2
3	240	30	6

Depending on the charging level (Table I) the user subscribes for with the utility company. Drive cycle, household load energy, grid energy cost, and renewable energy sources are the inputs of the system, whereas grid power and engine power profiles are outputs.

A. Offline optimization

To solve this optimization, a dynamic programming (DP) algorithm [5] is used. This algorithm is implemented in Matlab, and has been developed by Olle Sundström and Lino Guzzella [6].

The DP function when the series PHEV is disconnected from home, is shown in Figure 2 [7]. Here, P_{drive} is the drive cycle power given by (5). Also, F_a is the drag force, F_r is the rolling friction, F_g the grade resistance force, M_v is the mass of the vehicle, and v is the vehicle speed. When the series PHEV is connected to home, the dynamic programming function becomes Figure 3.

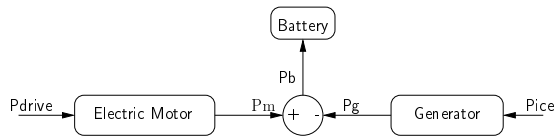


Figure 2. DP function when PHEV is disconnected to home

$$P_{drive}(t) = v(t) \cdot [M_v \cdot \frac{dv(t)}{dt} + F_a(t) + F_r(t) + F_g(t)] \quad (5)$$

Constraint variables use only one variable to increase the speed of the simulation. Therefore, the grid and engine power profile is implemented using one variable. The variable is used by the engine, when the vehicle is disconnected from home,

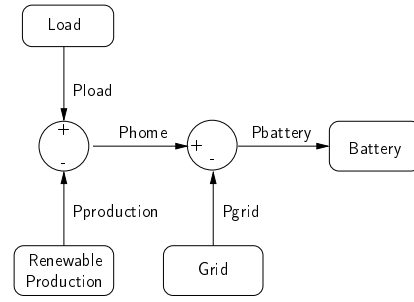


Figure 3. DP function when PHEV is connected to home

and is used by the grid, when the vehicle is connected to home. The power step is 100 W and the time-step is 1 second.

$$SoC(t+1) = \frac{-I_{battery}(t)}{Battery_{capacity} \cdot \frac{3600}{T_s} + SoC(t)} \quad (6)$$

The battery is considered as a dynamic system, which can be written as (6); where T_s is the time-step.

B. Online optimization

The online optimization uses the same algorithm as that of offline optimization. The DP runs on prediction data, such as renewable energy source production, consumption, drive cycle, and connection. The prediction of renewable energy sources data comes from weather forecast. The consumption prediction can be calculated by the previous days data. The connection prediction is entered by user and the drive cycle is assumed always the same.

The DP optimization calculates the P_{ice} and P_{grid} , which are the power output of the vehicle ICE and the power of the grid, respectively.

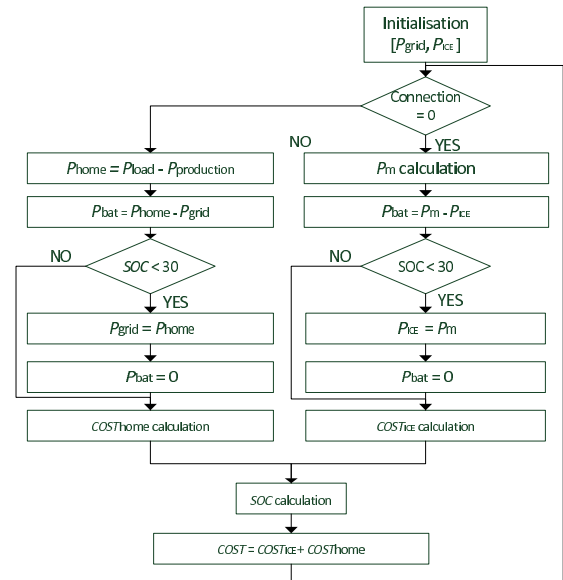


Figure 4. Main algorithm

This power is either positive, if the system predicts to buy energy, or negative, if the system sells energy from renewable

energy source. The DP runs in parallel of the main program (Figure 4) every hour, and when the connection prediction is different from the reality. It uses 6 hours of available data.

III. STUDY TEST CASES

This section describes two different examples. The first example shows the SOC variation in a 1-day simulation, during summer. The second example is a 1-week simulation.

A. Example 1: One day simulation during summer

This example is a 1-day simulation, starting at 8.00 AM, when the driver leaves home to go to the work, and finishes at 8.00 AM the day after. Thus, this simulation shows a 24-hour pattern. The user subscribes for level 1 battery charging (Table I) and standing charge using off-peak and peak price. From 2.00 AM to 7.00 AM and from 2.00 PM to 5.00 PM, grid energy costs 0.0864 €/kWh and at all other times, it costs 0.1275 €/kWh. Moreover, the selling price is 0.45€/kWh all day. Gas cost is fixed at 1.5€/liter.

The series PHEV characteristic are based on the Chevy Volt and are given in Table II. The three system inputs are shown in Figure 5, Figure 6, and Figure 7.

Table II
CHEVY VOLT CHARACTERISTIC [8]

Battery	16 kWh
Electric autonomy	60 km
Total autonomy	600 km
Battery voltage	320V-350V
Electric motor	111 kW

Obviously, the drive cycle is reversed from work to home. The solar datas production have been measured on July 1st, 2011, for 4m² PV panel, located in Belfort, France.

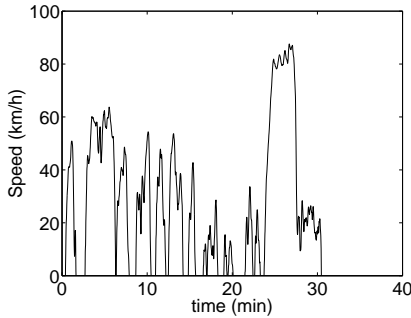


Figure 5. Japan Drive Cycle

1) *Offline*: Two simulations are described in Figure 8 and in Figure 9. Figure 8 starts with the series PHEV battery in discharged state. The control uses approximately 30% solar energy, 40% grid energy, and 30% engine energy, to supply the trip as well as household energy loads. Figure 9 starts with a fully charged battery. The simulation shows that the PHEV does not use the engine for propulsion. Also, the battery helps supply home loads, and the system sells energy to the grid.

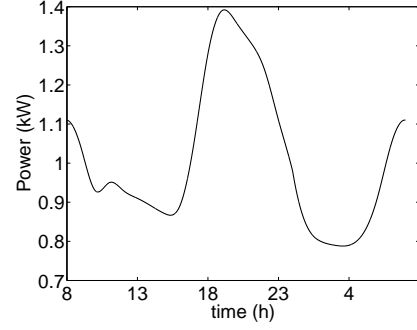


Figure 6. Household load power

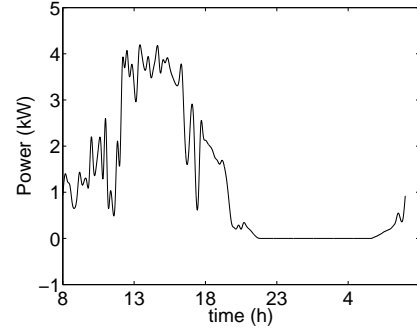


Figure 7. Solar power production

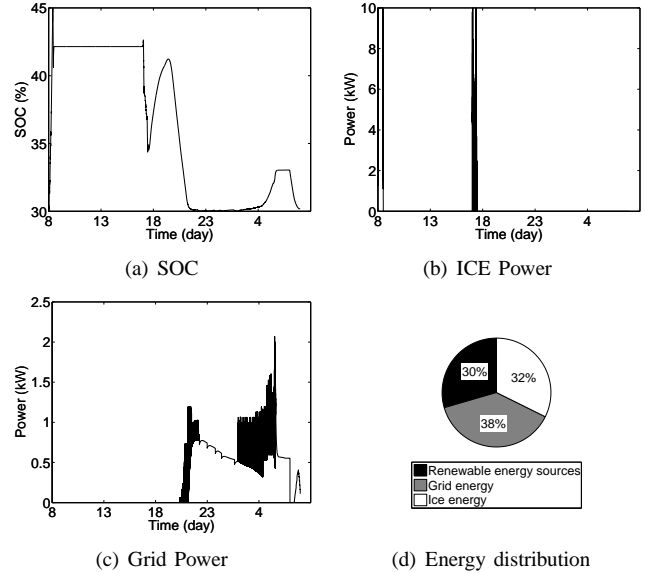


Figure 8. Offline output vectors for one summer's day with $SOC_{init} = 30\%$

2) *Online*: To simulate different conditions, the driver uses the car in the morning as was predicted. However, in the evening the user goes back home with 30 minutes delay. The drive cycle prediction is the real drive cycle, based on the Japan 10-15 drive cycle. The model can accept drive cycle prediction.

Scenario and real data, such as solar power production, household energy consumption, as well as drive cycle, are

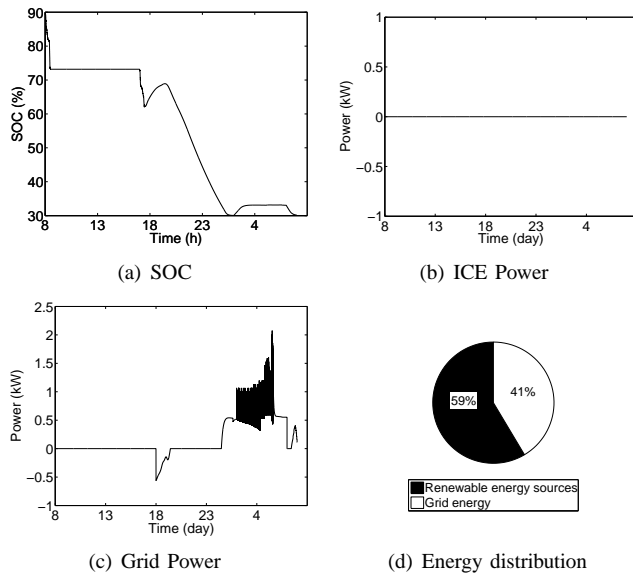


Figure 9. Offline output vectors for one summer's day with $SOC_{init} = 90\%$

the same as in the case of offline optimization example.

The optimized values of P_{ice} and P_{grid} are calculated using the solar prediction; Figure 10, and household consumption prediction; Figure 11.

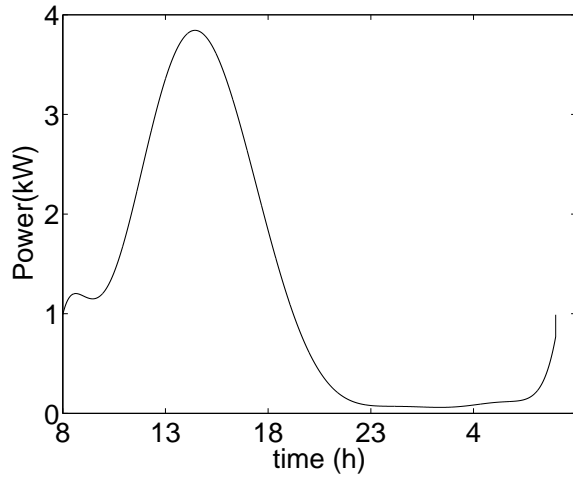


Figure 10. Solar production prediction

Two simulations shown on Figure 12 and Figure 13, present the discharge battery scenario and the charge battery scenario respectively.

The behavior in online and offline control strategy looks like the same except at the end of the day, where the battery is charged. This charging state exists because the online control strategy takes into account the beginning of the next day, whereas the offline control strategy finishes at 8 AM before the driver leaves.

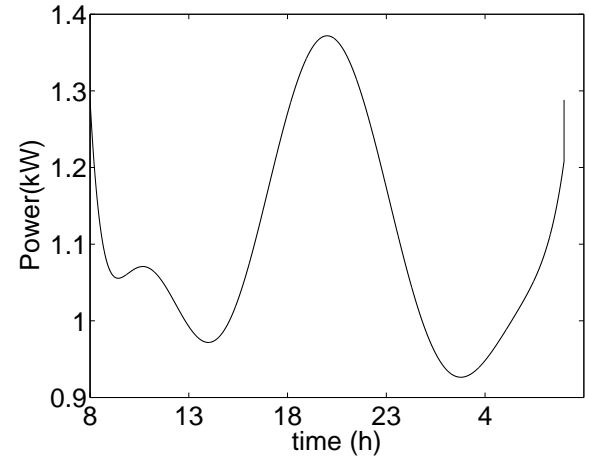


Figure 11. Household consumption prediction

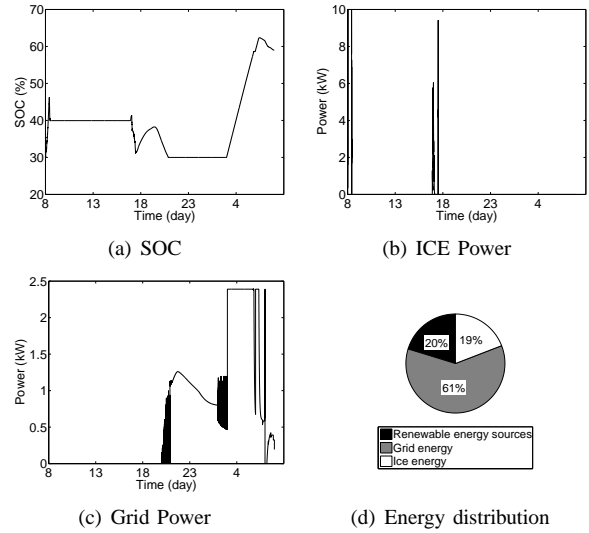


Figure 12. Online output vectors for one summer's day with $SOC_{init} = 30\%$

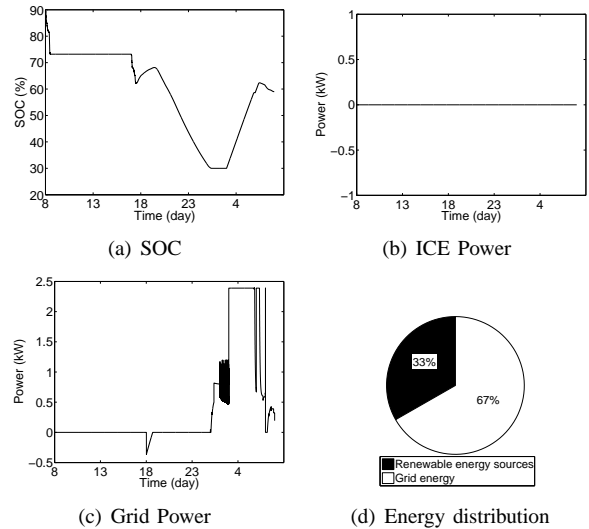


Figure 13. Online output vectors for one summer's day with $SOC_{init} = 90\%$

B. Example 2: One week simulation during summer

The vehicle travels from home to work and back home, as the first example shown in Figure 5, during the 5 working days. The solar production is measured in the first week of July 2011, in Belfort, France (Figure 14). The load consumption is repeated each day as shown in Figure 6.

1) *Offline*: In order to simulate a repetitive cycle, a constraint is added in this example, viz. the SOC_{final} is equal to the SOC_{init} . This constraint allows to show the battery charge at the end of the simulation.

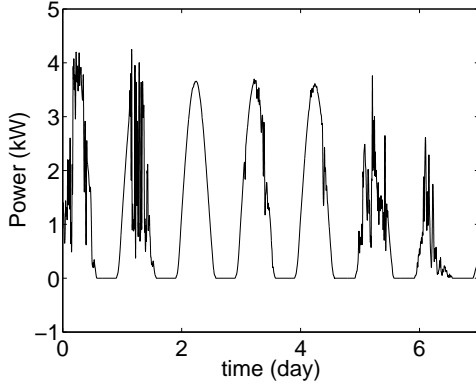


Figure 14. Solar power production during one summer week

Assuming that the first day is Monday and the last day is Sunday, the result shows that the vehicle and home use only grid and solar power energy to propel the vehicle as well as supply home consumers. As shown in Figure 15, during work days, the battery is used sparingly.

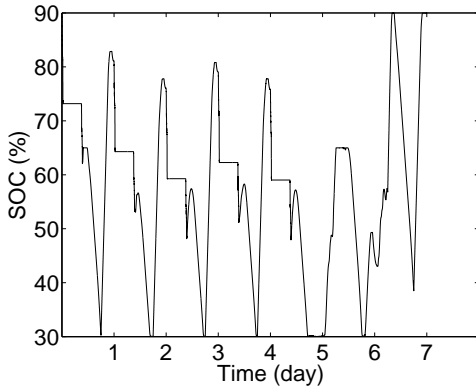


Figure 15. SOC offline optimization for one week

On Friday evening, the battery is completely discharged. During the weekend, the home charges the battery with the renewable energy source as well as grid, to prepare for the new week.

2) *Online*: The input data, which is used in online control strategy, are the same as offline control strategy. In this example, the driver uses the car randomly, to go to work and back home. However, the DP optimization uses the schedule

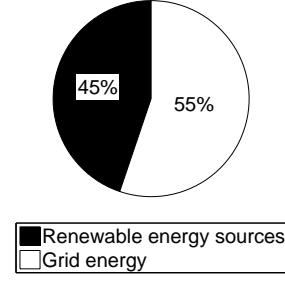


Figure 16. Energy distribution offline optimization for one week

to define the departure and arrival of the driver. The DP runs again, when it knows that the departure is delayed or advanced.

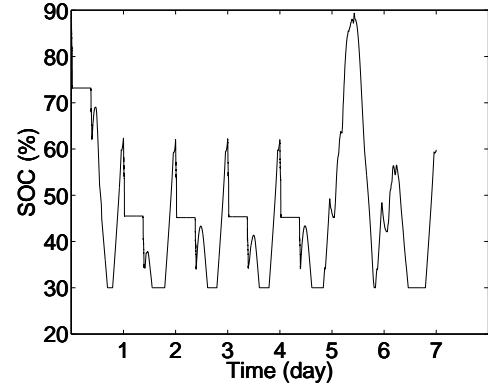


Figure 17. SOC online optimization for one week

Firstly, the online SoC profile seems the same as the offline profile except that there exists an amplitude change (Figure 17, Figure 15). For the offline control strategy the peak reaches at 80 % whereas in online control strategy is 60 %.

Moreover, on Saturday, the offline control strategy charges the battery completely whereas the online control strategy charges the battery only at 60 %.

In addition, the online control strategy has no constraint in terms of SOC_{final} . Therefore the battery is not charged at the end of the week.

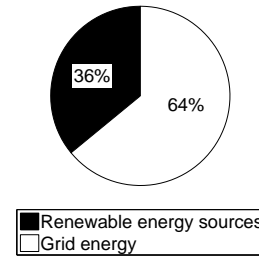


Figure 18. Energy distribution online optimization for one week

Finally, the online control strategy uses more grid energy than the offline optimization (64 % against 59 %). However, the ICE is not used in the both optimizations.

IV. CONCLUSION AND FUTURE WORK

In conclusion, a global offline as well as online optimization has been designed, to minimize the energy cost, when buying is positive and selling is negative. This optimization includes grid, local production from renewable energy sources, and PHEV

Results of different examples show, firstly, the battery behavior during the day and the week in summer. The model also works in winter. The results also show the overall energy distribution.

The peak power consumption is avoided, the battery supplies household consumption as well as grid albeit in less proportion. Moreover, the battery is charged after this peak power. Therefore any extra energy is used during this peak power. This system allows average out energy production. To complete the control strategy a cost function related to the state of health of the battery has to be implemented.

REFERENCES

- [1] S. Srinivasaraghavan and A. Khaligh, "Time management," *IEEE Power and Energy Magazine*, vol. 9, pp. 46–53, Jul. 2011. [Online]. Available: <http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=5899039>
- [2] S. Wirasingha, N. Schofield, and A. Emadi, "Plug-in hybrid electric vehicle developments in the US: trends, barriers, and economic feasibility," in *Vehicle Power and Propulsion Conference, 2008. VPPC '08. IEEE*, 2008, pp. 1–8.
- [3] J. Schlee, A. Mousseau, J. Eggebraaten, B. Johnson, and H. Hess, "The effects of plug-in electric vehicles on a small distribution grid," in *North American Power Symposium (NAPS), 2009*, 2009, p. 1–6.
- [4] I. I. Green, C. Robert, L. Wang, and M. Alam, "The impact of plug-in hybrid electric vehicles on distribution networks: A review and outlook," *Renewable and Sustainable Energy Reviews*, 2010.
- [5] S. G. Wirasingha and A. Emadi, "Classification and review of control strategies for Plug-In hybrid electric vehicles," *IEEE Transactions on Vehicular Technology*, vol. 60, pp. 111–122, Jan. 2011. [Online]. Available: <http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=5613206>
- [6] O. Sundstrom and L. Guzzella, "A generic dynamic programming matlab function," in *Control Applications, (CCA) & Intelligent Control, (ISIC), 2009 IEEE*, 2009, p. 1625–1630.
- [7] A. Ravey, B. Blunier, and A. Miraoui, "Control strategies for fuel cell based hybrid electric vehicles: from offline to online," 2011.
- [8] Chevrolet, "2012 chevy volt electric car features and specs," <http://www.chevrolet.com/volt-electric-car/features-specs/>. [Online]. Available: <http://www.chevrolet.com/volt-electric-car/features-specs/>