

Adaptive Energy Management Strategy Calibration in PHEVs Based on a Sensitivity Study

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ABSTRACT

This paper presents a sensitivity analysis-based study aimed at robustly calibrating the parameters of an adaptive energy management strategy designed for a Plug-in Hybrid Electric Vehicle (PHEV). The supervisory control is developed from the Pontryagin's Minimum Principle (PMP) approach and applied to a model of a GM Chevrolet Volt vehicle. The proposed controller aims at minimizing the fuel consumption of the vehicle over a given driving mission, by achieving a blended discharge strategy over the entire cycle. The calibration study is conducted over a wide set of driving conditions and it generates a look-up table and two constant values for the three controller parameters to be used in the in-vehicle implementation. Finally, the calibrated adaptive control strategy is validated against real driving cycles showing the effectiveness of the calibration approach.

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INTRODUCTION

The automotive industry is striving to reduce fuel consumption and emissions by improving the efficiency of powertrains and adopting new technologies towards the vehicle electrification. In this scenario, Plug-in Hybrid Electric Vehicles (PHEVs) are seen as a promising technology that will have a major impact to reduce fuel usage in the next several decades, [1]. PHEVs represent a compromise between Hybrid Electric Vehicles (HEVs) and Electric Vehicles (EVs), combining benefits of the two architectures. Similarly to a charge-sustaining hybrid vehicle, a PHEV is powered by two energy sources, gasoline and stored electric charge. PHEVs have significantly greater battery capacity than HEVs, and are characterized by the ability of charging the battery from an external source such as the electric power grid, solar power, etc. This external charging ability allows the battery to be depleted during vehicle operation and to be charged when the vehicle is parked, providing the opportunity of using electrical energy

in lieu of gasoline, and therefore displacing petroleum consumption, [2]. In a HEV, the battery is charged using the internal combustion engine (ICE) and regenerative braking, and the state of charge (SOC) is maintained in a relatively narrow range throughout the driving cycle, with the general objective of sustaining the battery SOC over a sufficiently long time horizon (for example, a trip), [3]. HEVs can achieve significant improvement in fuel economy by optimizing the power split between the battery and the ICE. The subject of optimal energy management of HEVs has been amply covered in literature, and is reasonably well understood, [4], [5], [6], [7], [8], [9], [10].

Energy management algorithms for PHEVs present additional challenges and opportunities: the fact that the battery is allowed to deplete its charge, and therefore is expected to operate over a much wider range of SOC, requires suitable attention to be paid to how the battery energy is utilized throughout the driving trip, [11], [12]. For example, one strategy might discharge the battery gradually

throughout the driving cycle (blended mode), while another strategy might discharge the battery completely, operating the vehicle in EV-only mode as long as possible, and then operate in charge sustaining operation. The SOC profile used by the control strategy during a trip has been shown to significantly affect the fuel economy of the vehicle in [13], [14], and [15].

This paper presents a solution to the optimal energy management of a PHEV that makes use of well-known principles in optimal control. The problem is solved by applying the Pontryagin's Minimum Principle, suitably modified to yield an adaptive strategy, hereafter called A-PMP. The adaptation of the control parameter of the PMP, called co-state, is realized by use of the idea proposed in [16], [17] for the HEV application, and further extended to the PHEVs in [18]. The open question left unsolved in [18] is the calibration of the parameters of the adaptation law to achieve robustness against different driving cycles for in-vehicle implementation.

In this paper, the Authors propose a calibration approach based on a sensitivity study carried out over a wide set of driving scenarios. The validation of the calibrated strategy is demonstrated over a real driving cycle. The strategy design and calibration study is done for the GM Chevrolet Volt. The vehicle model used in this study is presented in the next section.

VEHICLE DESCRIPTION AND MODELING

The GM Chevrolet Volt is a powersplit PHEV equipped with a planetary gear set and three clutches, [19], which connect and disconnect the on-board power sources as appropriate to implement various operating modes. The main components of the vehicle powertrain, depicted in Fig. 1, are:

1. MOT, which represents the traction electric machine and is a reverse machine;
2. GEN, which is the electric generator and can work in reverse mode, as well;
3. ICE, which is the internal combustion engine connected to the generator;
4. Planetary Gear Set, with three clutches (C1, C2, C3), whose configuration rules the mode of operation of the powertrain;
5. Battery pack (BATT), that provides electric power to MOT and GEN when needed.

Table 1 shows the vehicle main characteristics:

Table 1. Main characteristics of the vehicle

Curb weight	1715 kg
ICE (SI 1.4l) Rated Power	63kW@4800rpm
MOT Rated Power	111kW@4300rpm
GEN Rated Power	53 kW@4000rpm
BATT Max Power (Discharge)	110 kW

According to the different configuration of the clutches, the GM Chevrolet Volt powertrain can work in four modes of operation, [19], [20]:

- One-motor EV ($C1 = 1, C2 = 0, C3 = 0$)¹: only MOT drives the wheels, while ICE and GEN are switched off.
- Two-motor EV ($C1 = 0, C2 = 1, C3 = 0$): GEN is connected to the planetary gear set, hence, both MOT and GEN can supply power to the driveline.
- Range-extender mode ($C1 = 1, C2 = 0, C3 = 1$): MOT alone propels the wheels and the engine generator unit (GENSET) can supply power to the battery and extra power directly to the electric motor, if needed.
- Power-split mode ($C1 = 0, C2 = 1, C3 = 1$): All the onboard machines (i.e. MOT, GEN, ICE) are connected to the planetary gear set and can supply power to the driveline.

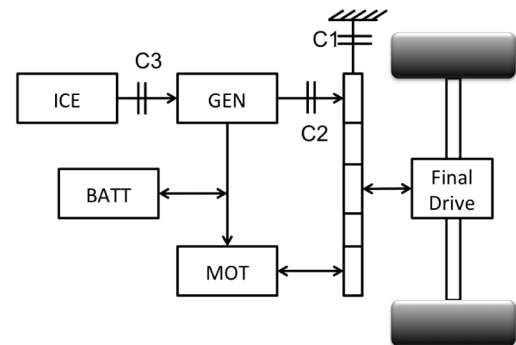


Figure 1. Chevrolet Volt powertrain and main components.

The vehicle simulator used in this study and realized in Matlab®/Simulink® environment is an improved version of the tool developed at IFP Energies Nouvelles and provided to all participants of the PHEV Control Benchmark competition held during the IFAC Workshop on Engine and Powertrain Control Simulation and Modeling, in Rueil-Malmaison, France, in October 2012 (<http://www.ecosm12.org>). A new battery pack model, described later in this paper, was implemented to replace the simplified one used in the competition. The model used in this study is based on experimental data provided for the LG Chem battery pack used in the GM vehicle, [21].

The forward-looking, energy-based vehicle simulator considers the longitudinal dynamics for the vehicle, the SOC battery dynamics, and employs stationary maps for the electric machines and the internal combustion engine, [19], [22]. The ICE is modeled using its brake specific fuel consumption map, while the electric machines, MOT and GEN, are modeled by means of their efficiency maps.

¹A value of 1 means that the clutch is closed, a value of 0 means that the clutch is open

Vehicle Dynamics

The longitudinal vehicle dynamics is dictated by:

$$m \frac{dv_{veh}}{dt} = \frac{T_{pwt} + T_{brake}}{r_{wh}} - mg \sin \alpha - c_0 - c_1 v_{veh} - c_2 v_{veh}^2 \quad (1)$$

where, m is the vehicle mass, v_{veh} the speed of the vehicle, T_{pwt} and T_{brake} are the torques, respectively, at the powertrain and the friction mechanical brakes and r_{wh} is the wheels radius; g is the acceleration of gravity, while the road grade variations (term $\sin \alpha$) represent a loss or a positive contribute, depending on whether the grade is positive or not; c_0 , c_1 and c_2 are coefficients, which aim at taking into account the energy losses due to the road load.

Battery

The battery pack used in the Chevrolet Volt is manufactured by LG Chem and has a configuration of 96S 3P Li-Ion cells, [23]. Table 2 summarizes all the main specifications of the storage system used in the vehicle, [21]:

Table 2. Battery characteristics

Total energy capacity	16 kWh
Total nominal voltage	390 V
Total peak current	400 A
SOC range	95%-30%

The battery model consists of a simple zero-th order equivalent circuit model, as shown in Fig 2, where V_{oc} is the open-circuit voltage source, R_{eq} represents the equivalent internal resistance and V_L is the load voltage across the cell terminals. The battery voltage output equation derives from the well-known Kirchhoff voltage law:

$$V_L = V_{oc}(SOC) - I \cdot R_{eq}(SOC) \quad (2)$$

where I is the current across the battery terminals². The battery parameters are a function of both SOC and temperature. In this study, the dependence of the open-circuit voltage on temperature is neglected, on the basis of experimental data, [24]. With regard to the resistance, the investigation is left to future studies and only the dependence with respect to the SOC is considered. The resistance is considered to assume the same values both in charge and discharge, [23].

From Eq. (2), the battery power is a function of SOC and is given by:

$$P_{BATT} = V_L \cdot I = V_{oc}(SOC) \cdot I - I^2 \cdot R_{eq}(SOC) \quad (3)$$

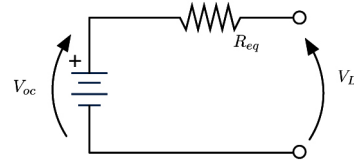


Figure 2. Zero-th order electrical circuit model of the battery.

The SOC dynamics is defined as:

$$\dot{SOC} = -\eta_c \cdot \frac{I}{Q_{nom}} \quad (4)$$

where η_c represents the coulombic efficiency of the battery, [25], and Q_{nom} is the nominal battery charge capacity. The SOC dynamics can be expressed as a function of the battery power, P_{BATT} , by solving Eq. (3) for the current, and replacing it into Eq. (4), to yield:

$$\begin{aligned} \dot{SOC} &= \\ &= -\eta_c \frac{V_{oc}(SOC) - \sqrt{V_{oc}(SOC)^2 - 4 \cdot P_{BATT} \cdot R_{eq}(SOC)}}{2R_{eq}(SOC)Q_{nom}} \\ &= f(SOC(t), P_{BATT}(t)) \end{aligned} \quad (5)$$

where $f(SOC(t); P_{BATT}(t))$ indicates the non linear mapping of the SOC dynamics.

Planetary Gear Set

In the Chevrolet Volt configuration, the trasmission consists of a planetary gear set, where the motor is connected to the sun, the generator to the ring and the transmission output to the satellite carrier, [20]. In addition, a differential with a fixed gear ratio (final drive in Fig. 1) connects the transmission output to the front wheel axle. The angular speeds of ring (ω_r), sun (ω_s) and carrier (ω_c) are linked by the kinematic Willis relation, [26]:

$$\rho \cdot \omega_r + \omega_s = \omega_c \cdot (\rho + 1) \quad (6)$$

with $\rho = 2:24$ representing the ratio between the number of teeth of the ring (N_r) and the number of teeth of the sun (N_s).

The torques relations for the gear set are condensed in the following Eq. (7):

$$\frac{T_r}{\rho} = \frac{T_c}{\rho + 1} = T_s \quad (7)$$

with T_r , T_s and T_c being the torques of ring, sun and carrier, respectively, and where:

²The current is considered positive in discharge and negative in charge. The same consideration holds for the battery power.

$$\begin{aligned}
T_r &= T_{GEN} + C3 \cdot T_{ICE} \\
T_s &= T_{MOT} \\
T_c &= \frac{T_{wh}}{f_d}
\end{aligned}
\tag{8}$$

with f_d the final drive ratio and T_{wh} the torque at the wheels.

PROBLEM FORMULATION

The design of the energy management strategy for the GM Chevrolet Volt is cast into a constrained optimization problem aimed at minimizing the fuel consumption over a given driving pattern, while providing the torque demanded by the driver, T_{wh} , at each instant of time, satisfying the following constraint:

$$T_{pwt} = T_{wh} \tag{9}$$

Formally, the optimization problem consists on minimizing the following cost function, J :

$$J = \int_{t_0}^{t_f} \dot{m}_{fuel}(u(t)) dt, \tag{10}$$

where $\dot{m}_{fuel}(u(t))$ is the instantaneous fuel consumption rate, $u(t)$ is the control variable, that is the battery power (P_{BATT}), and $[t_f - t_0]$ is the optimization horizon, corresponding to the length of the driving mission. For the sake of fluency the explicit dependence on time is here-after dropped.

The physical limits of the powertrain components are given by

$$\begin{cases}
SOC_{min} \leq SOC(t) \leq SOC_{max} \\
P_{BATT,min} \leq P_{BATT}(t) \leq P_{BATT,max} \\
T_{MOT,min} \leq T_{MOT}(t) \leq T_{MOT,max} \\
T_{ICE,min} \leq T_{ICE}(t) \leq T_{ICE,max} \\
T_{GEN,min} \leq T_{GEN}(t) \leq T_{GEN,max}
\end{cases}
\tag{11}$$

where, SOC_{min} and SOC_{max} are the minimum and maximum allowable states of charge, and $P_{BATT,min}$ and $P_{BATT,max}$ are the minimum and maximum thresholds for the battery power. $T_{MOT,min}$ and $T_{MOT,max}$ are the minimum and maximum possible torque values at a given angular velocity for the MOT, and, similarly, $T_{ICE,min}$ and $T_{ICE,max}$, and $T_{GEN,min}$ and $T_{GEN,max}$ are the same physical limits for ICE and GEN, respectively.

In addition to the physical limits of (11), the initial and final conditions of SOC, namely $SOC(t_0)$ and $SOC(t_f)$, must satisfy the following global constraints at $t = t_0$ and $t = t_f$:

$$SOC(t_0) = SOC_0; \quad SOC(t_f) = SOC_f \tag{12}$$

where, in this study, SOC_0 is assumed equal to 0.95 indicating that a fully charged battery is available at the

beginning of the trip and a SOC_f equal to 0.3 is selected to prevent battery wear at low SOC.

PONTRYAGIN'S MINIMUM PRINCIPLE

The energy management problem in a PHEV can be solved by using different approaches, including heuristic strategies, numerical optimization methods and optimal control theory, [27]. In this study, the latter approach is used by means of the Pontryagin's Minimum Principle.

The design of the GM Chevrolet Volt, as it is sold commercially today, is that of an Extended Range Electric Vehicle (EREV), that is a vehicle which operates as a pure electric vehicle as long as there is useful energy in the battery, turning into a charge sustaining HEV when the lower SOC threshold is reached. This mode of operation is often referred to as a Charge Depleting/Charge Sustaining strategy (CD-CS). In this paper a different approach is explored which, unlike the CD-CS strategy, provides a blended discharging mode of operation of the powertrain where the final desired value for the SOC, SOC_f , is only reached at the end of the driving cycle. The advantages brought by the blended strategy against the CD-CS have already been demonstrated in literature by [15], [28] and in [29], where the PMP was used to minimize a cost function representing the well-to-wheel production of CO_2 in a PHEV.

In the formulation of the PMP, the Hamiltonian function, H , is defined as follows:

$$H(SOC, u, \lambda) = \dot{m}_{fuel}(u) + \lambda \cdot \dot{SOC}, \tag{13}$$

where λ is the co-state and represents the only optimization parameter of the strategy. This equation expresses the contribution of both the energy sources in the vehicle: fuel and electric energy, [7], [30].

The global optimal solution of the problem is found by instantaneously minimizing the Hamiltonian:

$$u^*(t) = \arg \min_u (H(SOC, u, \lambda)) \tag{14}$$

while satisfying the following constraints:

1. state variable dynamics and global constraints on SOC:

$$\begin{cases}
\dot{SOC}(t) = f(SOC, u) \\
SOC(t_0) = SOC_0 \\
SOC(t_f) = SOC_f
\end{cases}
\tag{15}$$

2. instantaneous constraints on the control and state variables:

$$\begin{cases}
u_{min} \leq u \leq u_{max} \\
SOC_{min} \leq SOC \leq SOC_{max}
\end{cases}
\tag{16}$$