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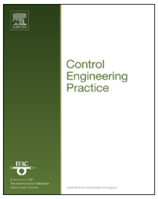

A control benchmark on the energy management of a plug-in hybrid electric vehicle

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ABSTRACT

A benchmark control problem was developed for a special session of the IFAC Workshop on Engine and Powertrain Control, Simulation and Modeling (E-COSM 12), held in Rueil-Malmaison, France, in October 2012. The online energy management of a plug-in hybrid-electric vehicle was to be developed by the benchmark participants. The simulator, provided by the benchmark organizers, implements a model of the GM Voltec powertrain. Each solution was evaluated according to several metrics, comprising of energy and fuel economy on two driving profiles unknown to the participants, acceleration and braking performance, computational performance. The nine solutions received are analyzed in terms of the control technique adopted (heuristic rule-based energy management vs. equivalent consumption minimization strategies, ECMS), battery discharge strategy (charge depleting–charge sustaining vs. blended mode), ECMS implementation (vector-based vs. map-based), ways to improve the implementation and improve the computational performance. The solution having achieved the best combined score is compared with a global optimal solution calculated offline using the Pontryagin's minimum principle-derived optimization tool HOT.

1. Introduction

Energy management of hybrid electric vehicles (HEV) is nowadays a more-than-ten-years-old field of research in control engineering (Baumann, Rizzoni, & Washington, 1998; Brahma, Guezennec, & Rizzoni, 2000; Hofman, Ebbesen, & Guzzella, 2012; Kleimaier & Schroder, 2002; Koot et al., 2005; Lin, Kang, Grizzle, & Peng, 2001; Paganelli et al., 2000; Salman, Schouten, & Kheir, 2000; Sciarretta, Back, & Guzzella, 2004; Sciarretta & Guzzella, 2007). Indeed, energy management is a control task since it consists in determining the setpoints (mostly, torque) to the various power converters (internal combustion engine, electric machines with their power electronics, mechanical transmission devices, electrical power converters, etc.) that constitute the HEV powertrain. These setpoints are chosen by the energy management strategy (EMS) in order to fulfil the driver's request and at the same time exploit the remaining degrees of freedom to obtain the most suitable powertrain behaviour. "Optimal" EMS that have been disclosed in these years are aimed at minimizing an objective function that typically represents the overall fuel consumption, but might include pollutant emissions, battery life degradation, under several constraints concerning battery charge,

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drivability, etc. In particular, charge-sustaining or autonomous HEV implies that the battery State Of Charge (SOC) at the end of a vehicle mission is required to be as close as possible to its initial value. A mathematical formulation of such a control problem has been posed in terms of optimal control (Ambühl et al., 2007; Hofman, Steinbuch, Serrarens, & van Druten, 2008; Kim, Cha, & Peng, 2011; Serrao, Onori, & Rizzoni, 2009; van Berkel, Hofman, Vroemen, & Steinbuch, 2012) and numerous practical implementations for various architectures such as parallel (Lin et al., 2001; Musardo & Rizzoni, 2005; Pisu & Rizzoni, 2007; Salman et al., 2000; Sciarretta et al., 2004; Sivertsson, Sundström, & Eriksson, 2011), series (Anatone, Cipollone, Donati, & Sciarretta, 2005; Pisu & Rizzoni, 2005), and combined HEV (Borhan & Vahidi, 2010; Cipollone & Sciarretta, 2006; Hofman et al., 2008; Liu & Peng, 2006) have been presented.

The class of plug-in HEV (PHEV), where the battery can be recharged from an external source (grid) also, has attracted less research than charge-sustaining HEV, although pioneering papers have already treated this topic in terms of optimal control and presented simulation or experimental results (Larsson, Johannesson, & Egardt, 2010; O'Kneefe & Markel, 2006; Stockar, Marano, & Canova, 2011; Serrao et al., 2013; Tulpule, Marano, & Rizzoni, 2009). The specific difficulty in this class of EMS is to generate an optimal discharge of the battery. Indeed it is known that a simple CD–CS strategy, i.e., a fully electrical operation (charge depleting, CD) followed by a Charge-Sustaining (CS) operation from when the battery is discharged onwards, although attractive as it allows presenting the HEV as an “electric vehicle”, is far from being optimal from a fuel economy standpoint. Therefore, progressive battery discharge (“blended-mode”) operation is expected to be the output of an optimal EMS.

While several EMS have been generally presented in the scientific literature, a way to compare them is obviously not generally available, since studied systems and driving conditions vary from case to case. Clearly, the ability to make direct comparisons between systems, employing these algorithms, would be highly beneficial for the scientific community to verify common claims concerning both performance (optimality) and implementability (flexibility or reusability, easiness of calibration and implementation, etc.) of EMS and focus future efforts in the most promising directions. Such comparison tools have been deployed for other control applications (Spencer, Dyke, & Deoskar, 1998) and consist of benchmark control problems that are typically solved using simulation models replacing real systems. As a second step, functional solutions might be benchmarked on physical systems as well. Recently, the Japanese automotive societies JSAE and SICE have jointly proposed a benchmark HEV control problem (Yasui, 2012) based on a simulator of a combined hybrid (Prius-like) vehicle and driver and aimed at challenging academic researchers.

This paper presents a benchmark PHEV control problem and analyzes a set of solutions. The benchmark was developed for a special session of the IFAC Workshop on Engine and Powertrain Control, Simulation and Modeling (E-COSM '12), held in Rueil-Malmaison, France, in October 2012. The participation of nine teams presenting their own solution demonstrated the interest in such initiative. All teams were provided with a fully functional simulator of a PHEV, and were to implement an EMS to optimize a set of criteria. The simulator (see Section 2) is of the quasi-static type and accounts for longitudinal vehicle dynamics and battery SOC dynamics, while the engine and electric machines are modeled using stationary maps. Solutions were to be submitted in the form of a Simulink block with a specific format (inputs/outputs/solver). The evaluation of the strategies was done on the basis of the fuel and energy consumption for two realistic driving cycles that were unknown to the participants, as well as acceleration performance and controller runtime performance (details in Section 3). In the cycle tests, the battery is completely charged at the beginning of the cycle and can be depleted at the end of the cycle. The participants were able to make use of some approximated information about the cycle, namely the total distance and average speed, which could be easily retrieved from a GPS device. Given the focus of the benchmark problem, this information was included in the simulator as perfectly known, albeit in practice it is affected by measurement uncertainties. A special jury, presided by the holder of the IFP School – Fondation Tuck Chair on Hybrid vehicle and energy management, defined the two test cycles and guaranteed the correct evaluation of the solutions to be benchmarked. The nine solutions evaluated are presented in Section 4, while Section 5 discusses the results obtained. The software developed for this benchmark will be made available on the web site www.ecosm12.org.

2. Simulator

Although a detailed description of vehicle propulsion systems would require the modeling of several dynamic phenomena, it has long been recognized (Guzzella & Sciarretta, 2013, Chap. 2) that for the purpose of fuel economy estimation, quasi-static models, i.e., based on efficiency maps measured under stationary operation of the various components, suffice to a large extent. For such a reason, quasi-static models are largely used to design and pre-assess energy management strategies of HEV, as per the literature cited within the paper. Of course, the mutual relationship between the EMS and typical transient maneuvers would not be represented by such models, but if the main focus is on the fuel economy, they can still reasonably serve to compare the global performance of different EMS. These are also the reasons why the present benchmark PHEV control problem is based on a quasi-static simulator.

The simulator provided implements a model of Chevrolet Volt, validated with published GM data, which are well reflected in the simulation results (Falières et al., 2011; Grebe & Nite, 2011; Miller, Holmes, Conlon, & Savagian, 2011; Parrish, Elankumaran, Gandhi, & Nance, 2011). The simulator implements three main blocks (Fig. 1): (1) driving cycle, which computes the torque demand based on the specified driving cycle, and also outputs the preview information (nominal distance and average speed); (2) control strategy (EMS), which was to be filled with the benchmark solutions respecting given input and output ports; (3) vehicle and powertrain model, which contains the quasi-static model of the powertrain and vehicle dynamics.

The participants had access to the content of the driving cycle and the vehicle model block, but they were not to be modified. Only their respective outputs could be used for developing the EMS, and only the controller block was to be submitted at the end.

2.1. Powertrain model: GM Voltec

The powertrain architecture powering the Chevrolet Volt consists of a power-split, planetary-based system, named Voltec and shown in Fig. 2. Three clutches (C1, C2, C3) allow connecting or disconnecting the internal combustion engine (ICE), the generator (GEN) and the main traction machine (MOT). Both electric machines can actually work in both motoring and generating mode, and for both of them the sign convention is that positive torque and positive electric power indicate motoring operation.

The powertrain can operate in the following modes (Falières et al., 2011; Grebe & Nite, 2011; Parrish et al., 2011):

1. *One-motor EV (C1 locked, C2 open, C3 open, engine off)*: MOT alone propels the vehicle, powered by the battery. The planetary gear