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An optimal regulation strategy with disturbance rejection for energy management of hybrid electric vehicles[☆]

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ABSTRACT

The energy management problem of finding the optimal split between the different sources of energy in a charge-sustaining parallel HEV, ensuring stability and optimality with respect to a performance objective (fuel consumption minimization over a driving cycle), is addressed in this paper. The paper develops a generic stability and optimality framework within which the energy management problem is cast in the form of a nonlinear optimal regulation (with disturbance rejection) problem and a control Lyapunov function is used to design the control law. Two theorems ensuring optimality and asymptotic stability of the energy management strategy are proposed and proved. The sufficient conditions for optimality and stability are used to derive an analytical expression for the control law as a function of the battery state of charge/state of energy and system parameters. The control law is implemented in a simplified backward vehicle simulator and its performance is evaluated against the global optimal solution obtained from dynamic programming. The strategy performs within 4% of the benchmark solution while guaranteeing optimality and stability for any driving cycle.

1. Introduction

A generic hybrid electric vehicle (HEV), regardless of the architecture considered, has two sources onboard that can supply the torque/power requested by the driver. HEVs use batteries, electric motors, regenerative braking and reduction of engine idling time to enhance a conventional internal combustion engine, thus achieving better fuel economy. The electric motor provides a portion of the power for propulsion, especially at high-load conditions when the vehicle is accelerating; some of the vehicle's inertial energy can be recaptured through regenerative braking systems and stored in vehicle batteries. According to Pesaran (2011), a possible classification of today's vehicles in the market can be given based on internal combustion engine size and electric machine size, as follows:

(1) Conventional internal combustion engine (ICE) vehicles;
(2) Micro hybrids (start/stop);
(3) Mild hybrids (start/stop + kinetic energy recovery);
(4) Full hybrids (mild hybrid capabilities + electric launch);
(5) Plug-in hybrids (full hybrid capabilities + electric range);
(6) Electric vehicles (battery or fuel cell).

In particular:

- In conventional vehicles, the ICE is the only source of power. For this type of vehicle the total power request at the wheel is entirely satisfied by the ICE An, Stodolsky, and Santini (1999), Miller (2003).
- A start–stop system automatically shuts down and restarts the ICE to reduce the amount of time the engine spends idling, thereby reducing fuel consumption and emissions. This feature is present in hybrid electric vehicles, but has also appeared in vehicles which lack of a hybrid electric powertrain. Non-electric vehicles featuring start–stop system are called micro-hybrids An et al. (1999), Miller (2003).
- In a mild hybrid vehicle generally an ICE is equipped with an electric machine (one motor/generator in a parallel configuration) allowing the engine to be turned off whenever the car is coasting, braking, or stopped An et al. (1999), Miller (2003).
- A full hybrid vehicle can run only using the engine, the batteries, or a combination of both. A large, high-capacity battery pack is needed for battery-only operation in the electric launch. In these vehicles a supervisory control is needed to provide

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coordination among the actuators in order to minimize fuel consumption An et al. (1999), Guzzella and Sciarretta (2007), Miller (2003). The objective of the present paper is to propose a new optimal regulation energy management strategy for a medium duty full hybrid truck.
- A plug-in hybrid electric vehicle (PHEV) utilizes rechargeable batteries that can be restored to full charge by connecting to an external electric power source Guzzella and Sciarretta (2007).
- A fuel cell vehicle (or electric vehicle) uses a fuel cell (or battery) to produce electricity and power its on-board electric motors Guzzella and Sciarretta (2007).

The objective of the energy management strategy in a HEV is to find the optimal torque/power split between the primary and secondary energy sources that minimizes a given objective function over an entire driving cycle.[2] The energy management problem in a charge-sustaining[3] HEV has been studied in the literature for over a decade (see, for instance, Brahma, Guezennec, and Rizzoni (2000); Pisu and Rizzoni (2007) and references therein).

In general, the energy management strategies can be categorized based on the feasibility of implementation in a real vehicle. The first category involves the use of classical optimal control techniques guaranteeing global/local optimality of the solution. Dynamic Programming (DP) assumes *a-priori* knowledge of the driving cycle and solves the problem backwards in time, considering all possible power split choices at each instant leading to the global optimal solution Brahma et al. (2000), Koot et al. (2005), Lin, Peng, Grizzle, and Kang (2003). On the other hand, Pontryagin's Minimum Principle (PMP) formulates and minimizes a Hamiltonian function (a function of the instantaneous cost and the state constraint) at each instant to obtain the optimal solution Anatone, Cipollone, and Sciarretta (2005), Delprat, Lauber, Guerra, and Rimaux (2004), Kim, Cha, and Peng (2011), Serrao, Onori, and Rizzoni (2009).

The second category of strategies consists of algorithms that are implementable in a real-vehicle, but they do not necessarily guarantee optimality. Equivalent Consumption Minimization Strategy (ECMS), adaptive energy management strategies and rule-based control strategies are in this category. The basic idea of ECMS is to reformulate the global optimization problem into a local optimization problem with tuning parameters. This method can give very good results, but the optimal equivalence factor, which depends on the driving cycle, must be determined *a-priori* using offline methods Paganelli, Ercole, Brahma, Guezennec, and Rizzoni (2001). To overcome this problem, adaptive ECMS methods have been proposed in the literature, for example, by adapting the tuning parameter of ECMS by predicting the driving cycle Musardo, Rizzoni, Guezennec, and Staccia (2005), or using pre-computed driving cycle-optimal equivalent factor correlations Gu and Rizzoni (2006), or using the correlation between equivalence factor and battery state of charge Chasse, Sciarretta, and Chauvin (2010), Kessels, Koot, van den Bosch, and Kok (2008), Onori, Serrao, and Rizzoni (2010). Rule-based strategies have also been very popular because of their simplicity in real-time implementation. The rules can be derived, for example, from the DP solution to the optimization problem Bianchi et al. (2010), Lin et al. (2003), Jalil, Kheir, and Salman (1997).

The following shortcomings in the HEV literature motivate the main contributions of the paper:

- Because the strategies that are based on classical optimal control techniques require *a-priori* knowledge of the driving cycle, they cannot be implemented in a real vehicle. They can be either used as benchmark solutions to perform comparative analysis of other implementable energy management strategies or to derive rules for rule-based strategies.
- The second category of strategies which can be implemented in a real vehicle need to be tuned for the intended driving conditions to perform close to the optimal solution.[4]

In this paper, we depart from these approaches and present a novel idea to design an energy management controller for a parallel HEV.

Linear-quadratic optimal control theory has been developed extensively over the past century; extension to nonlinear optimal control has broadened the effectiveness of such techniques. Because nonlinear controllers can effectively model the nonlinearities in the system and hence perform better than linear controllers for nonlinear systems, it is not surprising that significant effort has been devoted to developing the theory of nonlinear optimal regulation Bass and Webber (1966), Lukes (1969), Willemstein (1977).

In this paper, we develop a stability and optimality framework for charge sustaining HEVs, based on the results on nonlinear optimal regulation in feedback control problems involving non quadratic cost functionals, found in Bernstein (1993), Haddad and Chellaboina (2008). We aim at finding an analytical energy management strategy that can be easily implemented in a real vehicle assuring optimality and stability. It is shown that by suitably casting the energy management problem into a nonlinear optimal regulation problem and using an appropriate Lyapunov function candidate, it can be proved that the state-feedback based optimal control law (with respect to minimum fuel consumption) produces a charge-sustaining behavior. The control Lyapunov function[5] is also used in deriving an analytical closed-form expression for the optimal control law. The paper is an extension of the work proposed in Sampathnarayanan, Onori, and Yurkovich (2012) in the presence of external disturbances for the pre-transmission parallel HEV.

The paper is organized as follows: Section 2 describes the energy management problem in a pre-transmission parallel HEV along with the battery state of charge dynamics, integral and instantaneous constraints and Willans line based engine fuel consumption rate model. Section 3 casts the energy management problem into a nonlinear optimal regulation problem, where a set of sufficient conditions is proposed for the asymptotic stability of the origin and optimality of the control law with respect to the fuel consumed. Next, the optimal control law is implemented in a vehicle simulator and the results are evaluated against the benchmark solution from DP. Section 5 lists the main contributions of the paper and the intended future work.

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[2] In this work, we limit our focus to the problem of fuel consumption minimization, with no inclusion of drivability considerations. Typically, the gear shifting optimization pertains to the transmission control and it is not an objective of the supervisory control. The optimization of the gear shifting strategy would require the formulation of an optimal control problem which includes both continuous time and discrete time dynamics. In this work, we assume that the transmission controller operates independently to the supervisory controller, therefore the gear shifting strategy is treated as a known external input to the energy management system.

[3] A HEV in which the battery can be recharged/discharged only using the vehicle and not externally Miller (2003).

[4] Though rule-based energy management strategies are relatively easy to develop and implement in a real vehicle, a significant amount of calibration effort is required to improve its performance over a driving cycle. Furthermore these sub-optimal strategies are not necessarily scalable to other powertrain architectures and different component sizes.

[5] A control-Lyapunov function Pontryagin, Boltyanskii, Gamkrelidze, and Mishchenko (1962) is a function $V(x, u)$ that is continuous, positive-definite ($V(x, u) > 0\ \forall x \neq 0$), proper ($V(x) \to \infty$ *as* $|x| \to \infty$), and such that

$$\forall x \neq 0, \exists u \quad \dot{V}(x, u) < 0.$$

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