Control Engineering Practice 20 (2012) 547–558

Contents lists available at SciVerse ScienceDirect

Control Engineering Practice

journal homepage: www.elsevier.com/locate/conengprac

Design, implementation, and experimental validation of optimal power split control for hybrid electric trucks

Thijs van Keulen [a,*], Dominique van Mullem [a,c], Bram de Jager [a], John T.B.A. Kessels [b,c], Maarten Steinbuch [a]

[a] Department of Mechanical Engineering, Eindhoven University of Technology, Eindhoven, The Netherlands
[b] Department of Electric Engineering, Eindhoven University of Technology, Eindhoven, The Netherlands
[c] TNO Business Unit Automotive, Helmond, The Netherlands

ARTICLE INFO

Article history:
Received 19 February 2011
Accepted 28 January 2012
Available online 27 February 2012

Keywords:
Hybrid vehicles
Optimal control
Maximum principle
Hybrid power systems
Energy management

ABSTRACT

Hybrid electric vehicles require an algorithm that controls the power split between the internal combustion engine and electric machine(s), and the opening and closing of the clutch. Optimal control theory is applied to derive a methodology for a real-time optimal-control-based power split algorithm. The presented strategy is adaptive for vehicle mass and road elevation, and is implemented on a standard Electronic Control Unit of a parallel hybrid electric truck. The implemented strategy is experimentally validated on a chassis dynamo meter. The fuel consumption is measured on 12 different trajectories and compared with a heuristic and a non-hybrid strategy. The optimal control strategy has a fuel consumption lower (up to 3%) than the heuristic strategy on all trajectories that are evaluated, except one. Compared to the non-hybrid strategy the fuel consumption reduction ranged from 7% to 16%.

1. Introduction

Hybrid electric vehicles have, at least, two power converters instead of one: usually an internal combustion engine which can provide tractive power, consuming fuel with an irreversible process, and an electric machine which converts tractive power, reversibly, into electric power suitable for the battery, or vice versa. An important benefit of the electric machine is energy recovery during braking or driving downhill. This energy can be used at a later, more convenient, time to propel the vehicle. The electric machine also enlarges the maximum available tractive power and enables load shifting.

A supervisory control algorithm, i.e., the Energy Management Strategy (EMS), deals with the balanced generation and re-use of stored energy, using the clutch opening–closing, and the power split between engine and electric machine as control variables. Several contributions discuss the EMS design for hybrid vehicles, see Sciarretta and Guzzella (2007) for an overview.

It is known that, for a prescribed power and velocity trajectory, the global optimal solution can be calculated. In, e.g., Delprat, Guerra, and Rimaux (2002, 2004), Wei, Guzzella, Utkin, and Rizzoni (2007), Serrao, Onori, and Rizzoni (2009), Bernard, Delprat, Guerra, and Büchi (2010), and Ambühl, Sundström, Sciarretta, and Guzzella (2010) the necessary conditions for optimality are obtained with the Pontryagin Maximum Principle (PMP). In Paganelli, Ercole, Brahma, Guezennec, and Rizzoni (2001, 2002), Sciarretta, Back, and Guzzella (2004), Musardo, Rizzoni, and Staccia (2005), and Rodatz, Paganelli, Sciarretta, and Guzzella (2005) the related Equivalent Consumption Minimization Strategies (ECMSs) are applied to obtain the global optimal solution.

Causal strategies have no knowledge of the future power requests and vehicle velocity, and use only information available from past times and the present time. They rely, e.g., on heuristic rules (Hofman, Steinbuch, Van Druten, & Serrarens, 2007; Lin, Jeon, Peng, & Lee, 2004; Schouten, Salman, & Kheir, 2003) or on optimization that is based upon the observations obtained with the PMP and is solved in real-time (Ambühl et al., 2010; Borhan, Vahidi, Phillips, Kuang, & Kolmanovsky, 2009; Bernard et al., 2010; Delprat et al., 2004; Johnson, Wipke, & Rausen, 2000; Kleimaier & Schröder, 2002; Koot et al., 2005; Ripaccioli et al., 2009; Van Keulen, De Jager, & Steinbuch, 2008; Van Mullem, Van Keulen, Kessels, De Jager, & Steinbuch, 2010). The design of an optimal control based real-time implementable EMS results in (i) estimation of a multiplier function that adjoins the energy stored in the storage device to the fuel cost using real-time available information and (ii) optimization of a locally approximated Hamiltonian.

Frequently, the estimation of the multiplier is based on feedback on the current battery state-of-energy using a constant reference (Ambühl et al., 2010; Bernard et al., 2010; Delprat et al., 2004; Kleimaier & Schröder, 2002; Koot et al., 2005). Particulary in situations where the recoverable energy is large compared to the

* Corresponding author. Fax: +31 40 246 1418.
E-mail addresses: thijs.v.keulen@gmail.com (T. van Keulen), A.G.de.Jager@tue.nl (B. de Jager).

0967-0661/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
doi:10.1016/j.conengprac.2012.01.010

battery capacity a constant reference is restrictive since recovery and storage of energy lead to deviation in the state-of-energy.

Simulation results indicate the fuel consumption advantages of optimal control based strategies over rule-based strategies (see, e.g., Pisu & Rizzoni, 2007). Nevertheless, it is believed that, in most commercially available hybrid vehicles, rule-based strategies are implemented, although it is hard to find out exact figures. One reason industry prefers rule-based strategies is that requirements on available computational power are believed to hinder the application of real-time optimization.

This paper is concerned with the design, implementation, and experimental validation of optimal power split control in hybrid electric vehicles. The contributions are (i) the design and implementation of an optimal control based real-time implementable EMS, with a multiplier estimation which is adaptive for future energy recovery potential by accounting for the current kinetic and potential energy, on a standard Electronic Control Unit (ECU) in a hybrid electric truck, and (ii) an experimental validation of the implemented EMS.

The paper is organized as follows. In Section 2, the power split control problem is stated (Section 2.1), and optimal control theory is applied to derive necessary conditions of optimality (Section 2.2). Section 3 deals with the design of a real-time implementable strategy, which amounts to estimation of the multiplier function (Section 3.1), and approximation and optimization of a local Hamiltonian function (Section 3.2). In Section 4, the component characteristics of the test vehicle and implemented strategy are discussed. Experimental results are presented in Section 5, including an overview of the test setup (Section 5.1), tuning of the real-time multiplier estimation (Section 5.2), and evaluation of the performance at different trajectories, bench marked with a heuristic and a non-hybrid strategy (Section 5.3). Finally, conclusions and recommendations are given in Section 6.

2. Problem formulation and necessary conditions for optimality

In this section the power split control problem is outlined. The necessary conditions of optimality, obtained with the PMP, are presented.

A schematic overview of a hybrid electric drive train is depicted in Fig. 1.

The conversion of fuel power P_f to the engine output power P_p is modeled as a function of the power throughput:

$$P_f(S,\omega,P_p) = \begin{cases} P_{f,i} & \text{for } S=0, \\ P_{f,p}(\omega,P_p) & \text{for } S=1, \end{cases} \tag{1}$$

where S is a boolean variable modeling clutch opening, $P_{f,i} \geq 0$ is the fuel power during idling, $P_{f,p}$ is the fuel power if tractive power is delivered, and ω is the rotational velocity. If $S=0$ then $P_p=0$. When stop–start of the engine is possible, $P_{f,i}=0$, see Fig. 2a.

In many hybrid vehicle applications, the characteristics of the hybrid drive train components require a non-smooth modeling,

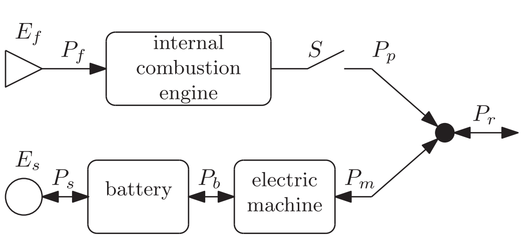

Fig. 1. Schematic overview of a hybrid drive train.

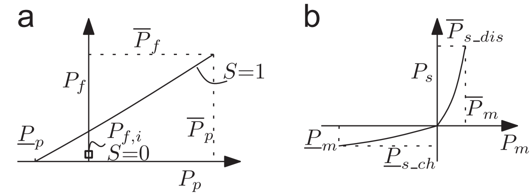

Fig. 2. Schematic cost functions of (a) engine and (b) electric machine and battery.

where charging and discharging is modeled with a non-smooth continuous function, see Fig. 2b. The combined conversion of storage power P_s to the electric power P_b, and of P_b to the mechanical power P_m is, therefore, modeled as a non-smooth function of the power throughput:

$$P_s(P_m,E_s) = \begin{cases} P_{s\_ch}(P_m,E_s) & \text{for } P_m \leq 0, \\ P_{s\_dis}(P_m,E_s) & \text{for } P_m \geq 0, \end{cases} \tag{2}$$

with $P_{s\_ch}(0,E_s)=P_{s\_dis}(0,E_s)$, in which P_{s_ch} is the storage power during charging of the battery and P_{s_dis} is the storage power during discharging of the battery, see Fig. 2b. The conversion process (2) could depend (smoothly) on the stored energy in the battery E_s. It is assumed that the influence of other variables on the conversion efficiency, e.g., rotational velocity of the electric machine, temperature, and ageing are known, and are incorporated in the power conversion function at time t. Note also that the drag power of the electric machine is always present (since decoupling the electric machine from the wheels is not possible) and is incorporated in the power request P_r such that $P_m=0$ if $P_s=0$.

It is assumed that P_r is a known and feasible driver input from the gas pedal only, such that the operation of the service brakes can be ignored and the system can be modeled with the independent scalar control P_m, and P_p becomes dependent by

$$P_p = P_r - P_m. \tag{3}$$

Further details of components are given in Section 4.

2.1. The power split control problem

Objective for the power split control is to minimize the fuel consumption E_f for a driving mission with arbitrary length, subject to constraints on the battery. This can be written as a standard optimal control problem, with the dynamics:

$$\dot{E}_f = P_f(\omega,P_r,S,P_m) \tag{4}$$

and

$$\dot{E}_s = -P_s(P_m,E_s). \tag{5}$$

Note that by using (3), P_f becomes a function of ω, P_r, S, and P_m.

Several constraints are present in the control problem: the power converters have (velocity dependent) power limitations as was already indicated in Fig. 2, the controls are bounded:

$$S \in [0,1] \tag{6}$$

and

$$P_m \in \mathcal{U}(\omega,P_r), \tag{7}$$

with

$$\mathcal{U}(\omega,P_r) = [\max(\underline{P}_m(\omega), -\overline{P}_p(\omega)+P_r), \min(\overline{P}_m(\omega), \max(\underline{P}_m(\omega), -\underline{P}_p(\omega)+P_r))], \tag{8}$$

the set of admissible controls, where $\underline{P}_p$ is the "drag" power of the engine at zero fuel consumption, $\overline{P}_p$ is the maximum engine output power, $\underline{P}_m$ is the maximum regenerative power, and $\overline{P}_m$ is the maximum motoring power.